

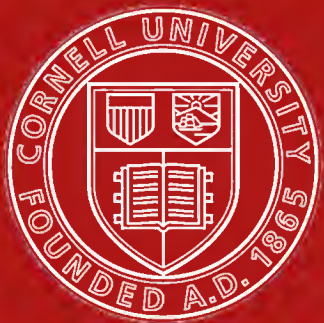
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GEORGETOWN COLLEGE OBSERVATORY.

THE PHOTOCRONOGRAPH

AND ITS

APPLICATIONS.

STORMONT & JACKSON,
PRINTERS,
WASHINGTON, D. C.
1894.



The papers contained in this volume are of a purely *descriptive character*. The experiments described therein are to be considered as merely preliminary, and do not pretend to show more than the feasibility of the methods explained. What the accuracy obtainable by them will be has to be decided by systematic observations.

One series of such observations, referring to the first paper, was finished some time ago and is nearly ready for publication; two others, referring to the fourth and fifth, are now in progress. Experiments suggested in the last paper are not contemplated here for the present.

GEORGETOWN COLLEGE OBSERVATORY, 1894.

J. G. HAGEN, S. J.

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PLATES.

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VIII.	CASTOR.

GEORGETOWN COLLEGE OBSERVATORY.

THE PHOTOCRONOGRAPH

AND ITS APPLICATION

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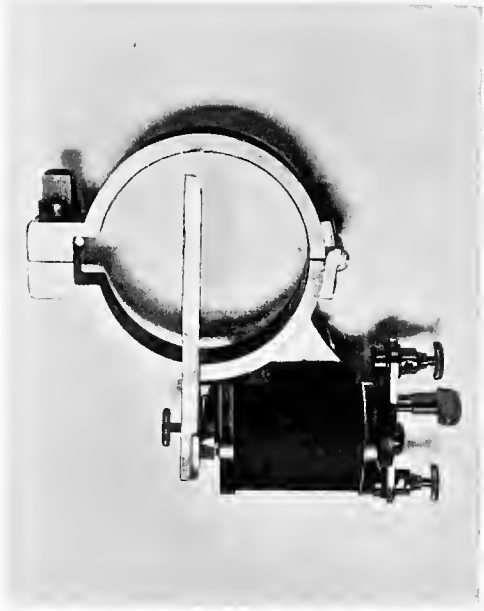


FIG. 1. THE PHOTOCHRONOGRAPH

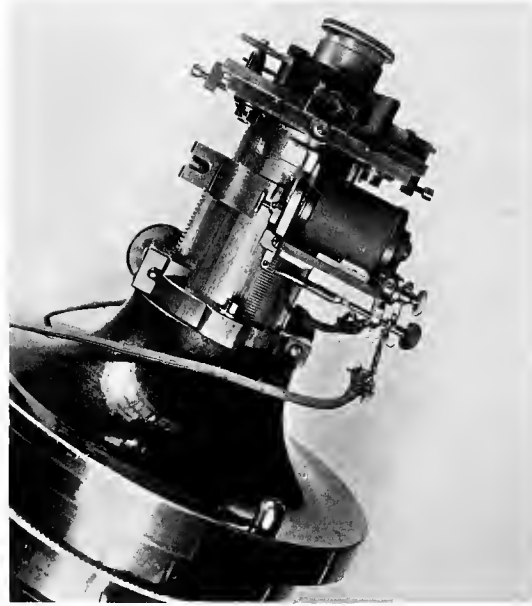


FIG. 2. THE PHOTOCHRONOGRAPH IN POSITION.

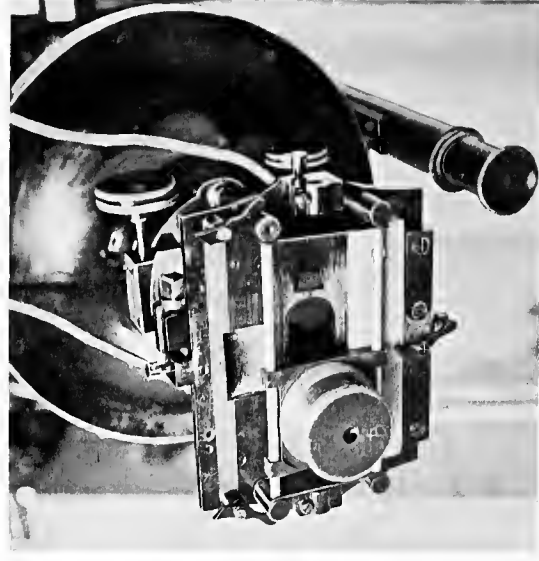


FIG. 3. THE PLATE HOLDER.

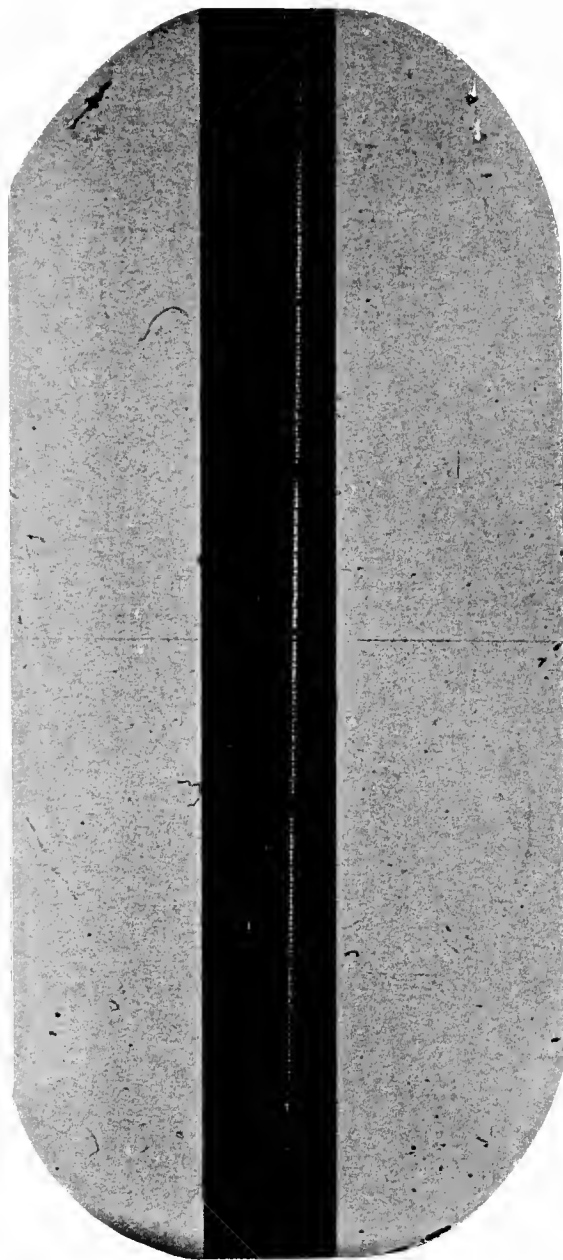


FIG. 4 TRANSIT OF SIRIUS \times 5.4

INTRODUCTION.

The observations described and discussed in the following pages had their origin in a visit made by Professor F. Bigelow and Mr. G. Saegmüller to this Observatory, in the summer of 1889. Their object was to use our 5-inch equatorial for a series of experiments in photographing star transits. All the resources of the Observatory were most cordially placed at their disposal, and on August 12th, 1889, the first apparatus was tested.

The experiments were repeated on August 26th with an improved apparatus, and were then broken off, for the time being, by the appointment of Professor Bigelow to the West African Eclipse Expedition.

The following account of these experiments was given in the "Woodstock Letters" for October, 1889 (Vol. 18, No. 3, page 402, Woodstock College Print, Woodstock, Md.):

"Important experiments have been made at the Observatory during the last two months for the purpose of removing the 'personal equation' in transit observations by means of photography. One night, Professor Bigelow, to whom the idea is due, and Mr. Saegmüller, an instrument-maker of Washington, were sitting with the Director of the Observatory at the table in the library and consulting as to the best way of putting the idea to a test. The long focus of the equatorial and the electrical connections for time-signals and incandescent lamps came in very handy for the purpose. The first camera was soon constructed and screwed to the eye end of the telescope, and a few evenings later the star Alpha Aquilæ was made to trace its diurnal motion on a small plate not quite two inches square, while the sidereal clock made the whole camera move in a vertical direction once every second. Finally, the spider-lines of the micrometer were photographed on the same plate by means of an incandescent lamp held for a few seconds before the object-glass. The development of the first plate, in the dark-room of the cellar, was watched with great expectation, and, to the satisfaction of all the bystanders, brought forth two parallel trails, broken into dashes, each representing a second of time, and the whole reticule of the micrometer lines. This first apparatus was soon superseded by a second, and the second by a third, each being improved as the experiments suggested. Further experiments will be necessary to perfect the details. This method of letting the sensitive plate take the place of the eye and of the chronograph seems to have a great future."

The Ertel Transit of the Observatory was subsequently handed over to Mr. Saegmüller for thorough repair and adaptation to this kind of photographic work.

The mercury contact, which had been temporarily attached to the pendulum of the sidereal clock, for our preliminary experiments, and which made and broke the electric circuit alternately for the space of a second at each make and break, was removed, as it had no pause to mark the beginning of the minute, and it was hoped that the ordinary spring contact of the clock might answer the purpose.

Shortly after, Professor George A. Fargis, S. J., was attached to this Observatory and at once put in charge of the Ertel Transit-instrument. The "Photochronograph" in its present shape and the improved method of photographing the reticule wires without injury to the star-trails are entirely his inventions.

At our request Professor Bigelow has kindly furnished us with a detailed account of his experiments prior to the summer of 1889. He courteously allows its insertion in this place.

Grateful acknowledgments are due to Mr. Thomas Whitney, a student of this College, whose industry and photographic skill were largely drawn upon in preparing the illustrations for this paper.

J. G. HAGEN, S. J.

GEORGETOWN COLLEGE OBSERVATORY,
February, 1891.

LETTER OF PROF. F. H. BIGELOW
TO THE
DIRECTOR OF THE OBSERVATORY.

WASHINGTON, *February* 13, 1891.

SIR: In compliance with your request, I send a brief historical sketch of the earlier experiments in photographing the transits of stars, made with the view of ultimately devising a process that will give time by transits, freed from the effects of personal equation.

The principal idea is to translate the phenomenon of an object *moving* over the field of view in a telescope, the instant at which it passes a thread being noted by eye and ear or by the chronograph, into a picture of the same which can be measured leisurely as a *fixed* object. The error of the personal equation depends ultimately upon the difference of time required by the eye to receive the impression of a bright object and to let the same go. Impression is more rapid than the letting go, and the relative times of retention vary with individuals and with the variable physical condition of the individuals. As stars are momentarily occulted behind a thread in transit, this element of retention throws the apparent place of the star beyond the thread; hence eye and ear observations, being taken at intervals *from* the thread, with the star in full vision, are more accurate and need a positive correction usually to be reduced to transits by chronograph taken *on* the thread.

A photographic plate reduces to a minimum this correction, both as to its amount and its variability, and whatever other corrections may be introduced by the process, they are mechanical and can be obtained by the discussion of results.

For the work of making a standard catalogue of bright stars for fundamental differential comparisons, for longitude determinations, for latitude, and also for physical observations in laboratories, it seems very important to eliminate by some process the error of the personal equation, which is in fact the greatest source of error in all such measures.

The first experiments to determine time by photographs of star transits were made by Professor E. C. Pickering, at the Harvard College Observatory, in January, 1886, the account of the work being given in the *Memoirs of the American Academy*, Vol. XL., p. 218.

The star images of the Pleiades were allowed to trail over a sensitive plate, the 8-inch Bache telescope being used, for known intervals of time. It was found that microscope settings on the marks could be made with a probable error of only 0^s.03, thus indicating the possibilities opened up by the method.

It now remained to apply it to transits in some way available in accurate reductions. There are two steps to be taken: (1) that which should connect the star trail definitely with the astronomical clock; (2) another enabling the transit to be referred to the collimation axis of the telescope. Both must be simple and free from all important objections. At the suggestion of Professor Pickering and Mr. Willard P. Gerrish, it was, in the summer of 1888, at the Harvard College Observatory, attempted to solve the first in the following way. A small plate was attached to the armature of a magnet by which a movement up and down, perpendicular to the star trail through a very small interval, could be communicated to it by making and breaking the circuit at fixed intervals, either by hand or by the clock, the latter requiring a commutator

in which the makes and the breaks should be of equal lengths. The effect was to leave on the plate a pair of dotted lines close together, the dots alternating in the perpendicular direction. The beginnings of the intervals and the endings were definitely marked, and settings of a micrometer thread could be made on them very accurately, the probable error being not greater than $0^s.02$ in second-intervals.

I constructed an apparatus for testing this process, the plate being kept in a paper holder inserted in a slide attached to the rocking armature which responded to the currents in the magnet. The telescope used was the 8-inch equatorial and the current was made and broken by hand. In the autumn Mr. Gerrish constructed a commutator by which the clock made the motions of the plate automatically.

Omitting for the moment mention of the second part of the process, for the sake of the chronological order, the next piece of apparatus was constructed by Mr. Saegmüller of Washington, D. C., at my suggestion, and was tried a few nights at the Georgetown Observatory in the summer of 1889, by the kindness of the Director, the Rev. Fr. Hagen, S. J. This piece embodied an important improvement, while retaining the alternating motion of the plate. A frame was made to carry a small plate-holder, which could be very readily interchanged with a common observing eye-piece. The star having been received into the field and adjusted by the direct vision, in 5 seconds the plate could be placed to receive the transit, this being a great practical improvement, as otherwise the adjustment of the star trail depended upon the finder to the telescope.

The Eclipse Expedition to West Africa, 1889, withdrew my own attention from the subject, and further development devolved wholly upon the Georgetown College Observatory.

Returning to the second division of the experiment, namely, the referring this trail to the middle wire and thence to the collimation axis of the telescope, without which the observation would be worthless, a number of combinations were discussed at the Harvard College Observatory. My first experiments consisted in using large threads which should interrupt the star trail by their own occultation of the star. This divided a continuous trail nicely, in two opposing cones of density, and was effective, but had obvious disadvantages for a transit instrument. Finally I found that by shining a light into the objective for two or three seconds the whole plate could be fogged down without obscuring the dotted trail, which seemed only to advance in its density, while the lines behind the threads failed to be fogged and retaining the original density of the unexposed plate, received definite edges suitable for microscopic measures by bisection or parallelism of threads. Small threads, even the ordinary ones used in the transit reticule of observatory instruments, are amply distinct for this purpose, and this part of the process leaves nothing to be desired.

There is no doubt that in a 6-inch transit instrument stars can be taken to the 4th mag., and wherever the elimination of personal equation is sufficiently important the utility of the method can hardly be doubted. My own belief is, however, that the chief field of usefulness will be found in the physical laboratory, where any amount of artificial light can always be used, and the automatic record can be made to assume any degree of accuracy desirable. It is known that many experiments in physics are afflicted with personal equation, and thus there is a hope of avoiding them by the introduction of this apparatus.

Very respectfully,

REV. FR. HAGEN,

Director of the Georgetown Observatory.

FRANK H. BIGELOW.

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PART I.

THE PHOTOCRONOGRAPH.

By G. A. FARGIS, S. J.

In an article entitled "Astronomical Photography," which appeared in the *New Princeton Review* for May, 1887, Professor Charles A. Young makes the following statement :

"In 1849 Faye suggested that photography might be utilized for meridian observation ; but it is only recently that any serious attempt has been made to put the idea in practice. Pickering, in this country, Lohse, in Germany, and Von Gothard, in Hungary, have all been experimenting, with more or less success. Pickering considers that the probable error of the transit of a star across a wire, viewed photographically, is only a little more than half that of a visual observation, and is *free from personal equation*. But the serious application of this method belongs to the future ; it may quite possibly work as great a revolution in the art of meridian observation as was brought about by the introduction of the electric break-circuit and the chronograph."

It is, therefore, with considerable diffidence that I venture to present a brief account of some experiments in the application of photography to meridian observations, the results of which would seem to indicate that the hopes expressed by Professor Young, if not actually realized are at least in a fair way to be so. These experiments were entered upon in July, 1890, and were carried on and perfected with but very little more than the ordinary transit-room equipment.

The following remarks contain, first, a description of the instrument with all its parts ; secondly, an account of the preliminary experiments, and, thirdly, the details of a night's observations :

A. DESCRIPTION OF THE INSTRUMENT.

1. The *Transit Instrument*, made by Ertel & Son, of Munich, was received at the Observatory in April, 1844. The object-glass is $4\frac{1}{2}$ inches in diameter, with a focal distance of about 78 inches. It was completely renovated by Mr. Saegmüller, of Washington, about a year ago, and is at present in good condition. The *micrometer box* is that usually furnished by the Munich firm, and a detailed account may be found in the volume published by the late J. Curley, S. J., the founder of this Observatory. The *finding-circle* on the clamp side reads zenith distances, while the other is adjusted for declination readings. A $1\frac{1}{2}$ -inch *finder*, of about

14 inches focal length, with one horizontal and five equidistant vertical wires, was firmly fixed to the transit, between the finding-circles, for the purpose of controlling the position of the star on the photographic plate. To balance the instrument, a *brass rod* with a *movable weight* was fastened along the upper tube, opposite the finder, so that the line joining the weight and the finder passed through the center of the cube, making the equilibrium *neutral*. On the sliding-tube, to which the micrometer box was attached, a *rack and pinion* movement was substituted for the usual sliding one, and parallel to it was engraved a scale, graduated to millimetres, from 1 to 70.

2. The *Photographic Apparatus* made by Mr. Saegmüller, of Washington, was confessedly imperfect, it being left to experience to modify and complete. It consisted of a heavy brass collar, which screwed on to the sliding-tube in place of the micrometer box, carrying a second and inner tube with a system of spider-lines, one horizontal and seven vertical, and four collimating screws. The collar terminated in a frame, having on the under edge a common **U** magnet, to the armature of which was attached a sliding frame, carrying the plate-holder, and, outside of this, an eye-piece. The *plate-holder* was of sheet brass, and so contrived that, when in place, the sensitive plate came within about two millimetres of the wires. This apparatus was to be connected with from four to six Daniell cells, and then put in circuit with the sidereal clock-relay, so that the motion of the plate depended on the *Gardner spring contact*, with which this clock is fitted.

The *modus operandi* of this imperfect photographic apparatus was as follows: Having collimated the wires, and focussed for visual rays by means of the mercury basin, the instrument was set on a star and clamped. The observer waited at the eye-piece until the star appeared in the field, and, with the slow motion, adjusted it to the centre. Then the plate-holder was inserted between the eye-piece and the wires, in the proper grooves, the slide withdrawn, and the current turned on. The clock relay broke the current every second for about one-tenth of a second, there being no break at the 59th second. Thus the beginning of the minute was marked by a pause. The plate, therefore, rose at each break, falling back as the current again flowed. This continued until the observer, at the finder, perceived that the star had completed its transit across the wires. The clock was then switched off, the instrument unclamped, tilted to a convenient position, and the observer held a light before the object-glass for a second or two for the purpose of photographing the spider-lines.

This accomplished, the developed plate showed, first, a continuous black line, marking the passage of the star, and, just above, a parallel line of dots, made by the one-tenth of a second

break at the end of each second. The 59th second having no corresponding dot, any particular second could be identified by counting backwards or forwards from that point. The light at the object-glass blackened the whole field, leaving the wires in white relief on a dark ground.

Transits of Alpha Lyrae and Alpha Aquilae were taken in this way with good results, and, at first sight, it appeared that the problem of the application of photography to meridian observations had at last received a practical solution, for we had on the negative what was equivalently a photograph of the meridian of the place and the position of the star for each second during the minute preceding and that succeeding the transit of the star, together with the precise moment of the transit. On closer examination, however, the method was found to involve some serious defects, both theoretical and practical. These were, in brief, the *motion of the sensitive plate*, the *weight of the moving parts*, and the resulting *uncertain rate* of the battery, a *photographic parallax*, owing to the distance of the sensitive film from the wires, and, lastly, the *partial obliteration of the star trail* in photographing the wires.

The gist of the difficulty appeared to be the *motion of the plate*, and this in spite of the ingenuity displayed by various experimenters in this field. It was decided that the *sensitive plate should not move*, the result of which decision was the invention of the *occulting-bar*. The present arrangement, which has been dubbed the "Photochronograph," is the outcome of a long series of experiments, in which the mechanical skill of Mr. Saegmüller, of Washington, has been of very great service.

3. The *new apparatus* (*Fig. 1*) consists of a strong brass collar, fitting closely to the sliding-tube, just behind the collimating plate, by means of a hinge and screw-bolt. To this collar is attached a **U**-shaped soft iron core, with a coil on one only of the arms, to diminish weight. The naked part of the core is bent back and up, so as to act on the armature from behind. The end of the core is encircled with a thin ring of cork, to diminish the force of the armature stroke. The usual adjusting and connecting screws are conveniently placed. A strip of steel, about two millimetres in width and two-tenths of a millimetre in thickness, is soldered to the armature, at right angles to its line of motion. This is passed through the apertures in the side of the focussing tube, intended for direct wire illumination, and stretches across the reticle. The coil, armature, and occulting-bar or shutter, are so fixed to the collar that, when at rest, the lower edge of the shutter (clamp east, and transit pointed south) is parallel to, and a fraction of a millimetre above the horizontal diameter of the reticle. The accompanying illustration, (*Fig. 2*), shows its position on the transit.

The *plate-holder* is merely part of the Ertel micrometer box. The *outer plate*, carrying the

eye-piece, the one next it with the movable wire, and the micrometer screws were removed from the box, together with the set of bevelled brass strips which formed the upper grooves, leaving only the plate containing the fixed wires and the one holding the collimating screws. To the outer surface of the former are attached horizontally, immediately over and about eight millimetres from it, two parallel steel bars holding the eye-piece in a sliding frame so as to command a view of the whole reticle cavity. (See *Fig. 3*.) The sensitive plate is inserted inside the parallel bars so as to rest flat against the reticle, and is held in place by a wedge of soft wood. When the wires are photographed by the object-glass illumination their image and that of the star are practically in the same focus, so that the thickening and displacement which constitute the photographic parallax are avoided.

In order to avoid this photographic parallax, the spider-lines had to be rejected, since it was practically impossible to handle the sensitive plate in the dark so close to the wires without constant and imminent danger of breaking them. They were accordingly replaced by a *glass reticle*. For reasons that will appear later, only *one vertical* and one horizontal line were cut in the glass, and these were not drawn through the middle of the glass, so that a vacant space was left around the centre of the cross. This prevents any cutting out of the dots in the star-trail. The horizontal wire is used merely for setting the stars and for adjusting the shutter parallel to the path of the star.

For the necessary purpose of identifying the clamp side of the negative, an arbitrary mark, in the present case a minute drop of ink, is placed on the reticle, on that side. This is printed on the negative when the wires are photographed, and the identification is complete.

Suppose, then, that connection be made with the sidereal clock-relay, and that a star begins its transit. When the current is turned on, the shutter falls with the armature, cutting off the light of the star. At the break, the shutter rises with the armature, uncovering the star for one-tenth of a second, and dropping again as the current flows. Hence the negative shows a simple line of dots, each representing one-tenth of a second exposure. As will be explained in the second part, the clock contact has been changed, so that the 29th, 57th, 58th, and 59th seconds do not break the current. Any second can, therefore, be readily identified. The oval blackened form shown in the illustration (*Fig. 4*), is the glass recticle, photographed by the light at the object-glass, and the white band across the center is made by the shutter, which intercepts this light when the wires are being photographed, thus preserving the star-trail from obliteration. This is accomplished by disconnecting the clock-relay and turning the current on directly to the apparatus. This holds the shutter down, right across the path just made by the

star, *completely protecting the photographed transit*. This position of the shutter also cuts off the horizontal wire, which does not appear in the photograph; but, as noted, its utility is confined to setting the stars and adjusting the shutter.

It might fairly be urged that the armature-stroke would impart a tremulous motion to the instrument, owing to the manner in which the apparatus is attached to the focussing tube. But the careful micrometric measurement of over 200 photographic transits shows no perceptible trace of any such error, and, if it were so, a very obvious arrangement would permit the application of this method, by a mere juxtaposition of the apparatus to the transit.

In this manner the objectionable features, which led to the rejection of the apparatus as at first constructed, would seem to be eliminated. The *sensitive plate does not move* from the beginning to the end of the operation, and, being securely wedged in against the reticle, there is little cause to fear *photographic parallax*. The *extreme lightness of the occulting-bar* and the *simplicity of the armature movement*, doing away with all transference of motion, reduces friction to a minimum, and makes the clock-beat and the shutter-movement practically synchronous. The *complete protection of the star-trail* against the illumination necessary for photographing the wires, as just described, is also a distinctive feature of this method. For these reasons, it may be conceded that the instrument described has a valid claim to the name of "Photochronograph," since it actually registers on the sensitive plate the time of the transit of a star.

4. It may be of service to mention some of the *accessories*. The sensitive plate, when in position for a transit, was protected by means of a heavy cloth bag, carefully secured over the eye end of the transit, completely enclosing the whole apparatus. Two *lantern boxes* with bent chimneys, and holding kerosene lamps, were provided; one for photographing the wires was made light-tight; the other had ruby glass on three sides, giving sufficient light for consulting the star-lists and taking notes. A *reading lantern* for the level had to be ready. The *battery* is composed of four Daniell cells for the photochronograph and one for the sidereal clock-relay. An extra battery of four cells is in readiness in case the first shows any signs of weakness; and, on nights when the observations were prolonged, the batteries were changed frequently. The wires connecting the photochronograph with the terminals on the top of the west pier are made self-detachable to avoid accidents when reversing.

The *switch* used is a two-point one, and is connected with three wires running under the floor from the switch-board in the clock-room to the transit-room. Two of the wires start from the binding-posts labelled "S. C. D." (Sidereal Clock Direct), and the other from the clock contact,

forming two loops at the command of the operator. The switch is conveniently situated near the transit pier, and so arranged that on one point the sidereal clock-relay and the photochronograph work as described; by the second the current is turned to the photochronograph alone, or by dropping the lever between the two points both currents are broken. This last is, of course, the usual position between the observations.

5. The measurable photographic transit once obtained, a *micrometer-microscope* had to be devised. After considerable experimenting, the present arrangement proved suitable. A heavy, cast-iron, Y-shaped stand, with the upper portions of the arms accurately planed, was fitted, on one side, with a movable stage for carrying the negatives. It was provided with rack-work for focussing and centering. The other arm was fitted with a tube, carrying on one end an objective of about six inches focal distance, and on the other was placed the micrometer of our old five-inch equatorial by Troughton & Simms, originally devised for double-star work. It has one fixed horizontal and two movable vertical wires with position circle. The tube just mentioned is, in fact, the centering apparatus of the same equatorial, and is provided with two screws for vertical and horizontal adjustment. A full discussion of this arrangement, the accuracy of measurement attainable, and a critical examination of some results already obtained, will be found in the second part.

The following section contains a brief account of some interesting and essential experiments concerning the actinic focus and the sensitive plate.

B.—PRELIMINARY EXPERIMENTS.

1. The first requisite was an *actinic focus*, which was necessarily imperfect in a lens corrected only for visual rays. So, the visual focus being carefully determined at a point indicated by 39 mm. of the scale on the sliding-tube, various positions of the plate were tried, to cut, if possible, the *plane of the minimum spherical aberration of the actinic rays*. This was found roughly to be somewhere between 45 mm. and 35 mm. of the sliding-tube, and measures were taken to determine its position as accurately as possible.

For this purpose the sliding-tube was set at 45 mm., and, whilst the star was crossing the plate, the tube was moved in as far as 33 mm. in seven successive steps of 1.7 mm. each. The equality of these steps was secured by means of the rack and pinion, the teeth of the rack-work being 1.7 mm. apart. The step was made by making a tooth coincide exactly with the collar of the main tube, and, placing a strip of sheet metal in the succeeding tooth, the tube was moved in by the screw until stopped by the striking of the metallic strip against the collar, which

diminished the length of the tube exactly 1.7 mm. Some such device was necessary, as the whole operation had to be carried on in the dark, and the graduated scale could not be employed, except to indicate the termini. This occupied one pair of hands, so a second observer was stationed at the slow-motion screw, and at each step of 1.7 mm. he turned the screw one revolution to the right and left alternately. Between each step, from 10 to 30 seconds were counted, according to declination. At the starting-point, 45 mm., the star was allowed to impress its image on the plate for some seconds before the movements just described were begun. Each star thus described eight trails as follows:

	43.3		39.9		36.5		33.1
45.0		41.6		38.2		34.8	

The sharpest lines were invariably at 41.6 mm., or 39.9 mm., the difference being scarcely appreciable. By suitable variations of this method, taking the mean of numerous observations, it was found that, for an average temperature of 40.0° F., the mean actinic focus was indicated by 41.5 mm. on the sliding-tube. The plane, therefore, of the minimum spherical aberration of the actinic rays is 3.5 mm. further from the object-glass than the visual focus, a case quite analogous to the one mentioned by Konkoly, regarding his own instrument. (See V. J. S., 25 Jahrg., II. Heft, p 136.)

2. The next thing to be considered was the *sensitive plate*. The problem offered for solution was to photograph a fourth-magnitude star, or lower, if possible, with an exposure of about one-tenth of a second, and to develop the impressions thus obtained, so as to render them susceptible of measurement with the micrometer-microscope. To meet the various exigencies of magnitude, declination, colour, and actinic power, plates of different degrees of sensitiveness were required; for the size of the dots depended on the magnitude, the distance between them, on the declination, and their intensity, in most cases, on the colour and actinic power, although there were some anomalies. Carbutt's or Seed's No. 23 answer well for *1st-magnitude* stars anywhere below +30°; above that a slower plate must be used, to avoid fogging the space between the dots. Carbutt's Orthochromatic No. 27 gives good results. A *2d-magnitude* star below +30° takes a very quick plate—Cramer's No. 40, for example, or Carbutt's No. 27. Above +30° a slower plate gives the dots more distinctly as they become smaller, and the danger of fog is eliminated. For stars between 2.0 and 3.5 *magnitudes*, and *above* +30°, a very quick plate is required, and for these same magnitudes *below* +30°, or for *4th-magnitude* stars of any declination, the very quickest plates yet made are not always reliable. The "C" plates of Messrs. Cramer, of St. Louis, have given the best results up to the present. With them photographic transits have been taken of 4th magnitude stars above +30°, and of 3.3 down to the Equator.

These remarks regard *measurable transits* only, for traces of fainter stars are occasionally visible even on less sensitive plates. The fourth magnitude is then for the present the limit of this method, at least for the exposure of one-tenth of a second. It is obvious, however, that the photochronograph affords an exposure of nine-tenths of a second, which is available for stars of lower magnitude. But few experiments have been made in this direction, as the brighter stars have first claim on our attention.

The size of plate found most convenient was $1\frac{1}{2}$ by $2\frac{1}{2}$ inches, which unusual size was courteously furnished by the Messrs. Cramer, of St. Louis, and Carbutt, of Philadelphia.

3. As may be readily imagined, the *development* of these plates offered peculiar difficulties. The very faint impressions under so short an exposure, left by the stars below 2.5 magnitude, required very prolonged development to make them measurable. Then, too, the progress of development could not be ascertained, even with a pocket lens, so that some modification of the ordinary photographic method of development became necessary. Experience shows that in this particular case a prolonged development in a concentrated solution of *eikonogen* is well adapted for the purpose. It seems to build up the image better than anything else, and the development can be pushed ahead for hours without fog, and with a constant increase of intensity; besides, it does not soil the fingers, and can be used again and again. The plan adopted is to develop until the plate begins to fog, and even a little beyond, since a certain amount of fog does not interfere with the micrometric measurement. As a general rule the plates are developed for from $1\frac{1}{2}$ to 2 hours, and even longer for some fainter stars—in fact, the longer the better, since the time of exposure being fixed, the development must do the rest. In this way, the transit of some 60 stars, down to the 4th magnitude, were taken from November to March, including about 700 photographs, of which over 300 gave measurable transits.

C. A PHOTOGRAPHIC TRANSIT.

1. As the photochronograph is not an idea merely, but a machine in actual working, a description of a night's observations, taken in this novel way, may prove of interest. Previous to the actual working hour, a number of necessary *preparations* must be made.

Collimation would seem to come first on the list, but, in the present instance, there is no question of determining the collimation visually, except for an approximate adjustment, since the sliding tube is clamped about 3 mm. outside the visual focus, and the eye-piece, in consequence, cannot be pushed in far enough to give a good image of the collimating object. The operation, then, must be left to the sensitive plate. A pair of common collimators would prob-

ably be the best means of impressing the collimation error on the plate, in the form of two parallel lines, the distance between which would be measured, after development, by the microscope. The idea of photographing the direct and reflected images of the reticle over a mercury basin does not, perhaps, imply an impossibility, but it must, for the present, be left an open question.

The *pivots*, which are kept covered with vaseline, are carefully cleaned, the instrument being raised from the **Y**'s for that purpose by means of the reversing stand. The **Y**'s receive due attention, as also the supports of the striding-level. The *batteries* and all the connections are then tested, and the movement of the occulting-bar adjusted by the proper screws. The *lamps* for room-work and for photographing the wires are prepared, together with a special lamp for level reading. *Sensitive plates* of different degrees of sensitiveness, *black cloth* and *boxes* for stowing away the plates to be developed ; *wooden wedges* for securing the plates in the plate-holder, *note-book* and *star-list* must be on hand. The ordinary observing-chair is removed and a low cushion provided between the piers. Particular attention is paid to the arrangement for photographing the wires, lest it should admit stray light into the room or introduce hot-air currents.

About an hour before the observations begin, the *roof-shutters* are opened and secured, the coverings and caps removed from the instrument, and the *hanging-level* is put in position. Whilst the outer and inner temperatures are equalizing, most of the details just mentioned can be attended to without loss of time. Then the level is read, west and east readings being made, west counting as positive, and east negative. These readings are recorded, with the date, position of the clamp, temperature, state of the atmosphere, and the sidereal time of the observation.

The instrument is now set on any star about to cross the meridian. The current is switched on to the sidereal clock, and an *eye-observation* is made of the working of the photochronograph. This is of prime importance, excluding as it does all doubt as to its actual performance during the observations. No field-illumination is used. By means of the sliding eye-piece the eye of the observer takes the place, for the nonce, of the sensitive plate, and the working of the shutter is carefully observed. The star image, though blurred from being out of visual focus, is sufficiently distinct for the purpose. The successive appearances and disappearances of the star are regulated with the slow-motion screw ; care being taken that the appearance is unmistakable, the disappearance complete, and this for the whole course of the transit. This operation affords the observer a striking illustration of his personal equation. For the armature beat at the appearance and disappearance of the star enables him to appreciate the slowness of the retina

in receiving and losing the star-image; reminding him that the star is not seen where it actually is, but where it was just a moment before: this, by way of parenthesis. The shutter then once adjusted, we are supposed to be ready for a *photographic transit*.

2. A star is *chosen* from a list prepared according to the actinic power of the object-glass. In the present instance the lower limit is fixed at 3.5 magnitude, except, of course, for azimuth stars, where the fourth magnitude is quite attainable. The star-number is recorded, together with the magnitude, color, and declination, which entry serves as a guide when developing the negative. A sensitive plate is selected according to the principles just laid down, and numbered with lead pencil, and placed in readiness for the plate-holder.

The transit instrument is now *set* on the star and clamped. By means of the finder the star is observed, until, by its position on the vertical wire, it is seen to be on the point of entering the field of the reticle. The current is then turned on at the switch, the eye-piece slid over to the west side of the reticle, and, with the slow motion, the star is adjusted to the armature edge of the occulting-bar, for a one-tenth second exposure, and to the other edge, if a nine-tenth second exposure be desired. This settled, the plate is slipped in flat against the reticle, the wedge pressed in between the back of the plate and the parallel bars, and the bag securely fastened.

The time of passage across the reticle varies, of course, according to its size and the declination of the star. In the present instance an equatorial star takes four minutes to cross.

The transit over, the clock circuit is broken and the current turned on to the photochronograph alone. This brings the shutter down and protects the star-trail whilst the wires are being photographed. The transit instrument is unclamped, tilted to a convenient position, and a light is held to the object-glass. Here a certain amount of discretion is supposed. The time of exposure must be regulated according to the style of plate and the quality of light. With a common kerosene lamp, one second suffices for Cramer's "C" plates, two or three for Carbutt's "Eclipse" No. 27, and ten to fifteen for Carbutt's Orthochromatic No. 27, which are the three grades ordinarily used. This done, the current is broken, the plate removed and placed in the box prepared for it.

In this way some ten or fifteen stars are taken, including always three or four azimuth stars. The *level* is then read twice, as in the start; the transit instrument is *reversed* and the level again read twice, the results being carefully recorded. This reversal being amply sufficient to determine the *collimation* constant, the transit instrument remains in this position for the rest of the night, level readings being made every hour, and an average of one *azimuth star* in five being secured. The observations over, a final level reading is made, the temperature

noted, the plates carefully boxed, protected with black cloth coverings, and put aside for development.

On an average, with the outfit just described, about *six stars an hour* can be photographed in this way, and experience shows that about five hours of such work is very near the limit of ordinary endurance. Lest the results of the whole night's work should be lost, more stars for azimuth and collimation purposes are taken than are usually considered requisite, for, unless under certain very favorable conditions, it is not easy to forecast what kind of trail will be left on the plate by any given star. The inequalities of the most perfect sensitive film, and the mischievous effect of atmospheric influences and disturbances on a feeble star-ray, during an exposure of one-tenth of a second, will account for most of the disappointments. A greater number of stars might be secured in a given time, were the plate exposed only during the half-minute preceding and that immediately succeeding the passage of the meridian. But it is a great advantage to have the record of as many seconds as possible for the purpose of micrometer measurement, and, at times, it is quite indispensable for identifying the pauses.

It may be well to remark that the slight irregularity of star trail in the beginning of the transit, as shown by three or four of the dots in *Fig. 4*, is owing to the fact that the occulting-bar is already in motion before the sensitive plate has been adjusted to the plate-holder.

The entries made in the note-book are transferred as soon as possible to a regular *journal*, in which are also recorded detailed accounts of the results of development. Each negative, after the usual processes, is enclosed in a numbered envelope of convenient size and put away in suitable trays for measurement. In this manner every single negative, even if unfit for the micrometer, is carefully preserved, the knowledge derived from a discussion of these failures being often quite as valuable as that afforded by plates of greater apparent worth. About 60% of all the negatives are fit for the micrometer, and, up to the present, over two hundred photographic transits, taken in the manner just described, have been carefully measured.

PART II.

RESULTS OF THE PHOTOGRAPHIC TRANSITS.

By JOHN G. HAGEN, S. J.

The following account of the measurements and reductions of our photographic transits contains all the details necessary for a sound judgment on both the advantages and the defects of this method.

It is divided into four sections : The first treats of the microscope and its errors ; the second of the methods of measuring ; the third of that of reduction ; and in the fourth, these methods will be practically illustrated in a specimen transit.

A.—THE MICROSCOPE.

The eye-pieces of the micrometer of our 5-inch equatorial, adapted for microscopic measurement, as previously described, had *magnifying powers* of 38 and 33 diameters, with fields of 50 and 80 revolutions respectively. Both eye-pieces have been used in the measurements given below.

The *screws*, however, by which the two vertical wires were moved from the middle of the field towards both ends, had to be rejected on account of their large periodic error, not to speak of the inconvenience of using two threads, and these not even parallel. A single screw was then inserted into the old micrometer box, and its *errors* determined in the following manner :

1. Periodic Errors.—Only the two revolutions nearest the middle of the comb ($=15^{\text{R}}.0$) were examined, for reasons which will appear below. Two particles of dust on a glass plate, nearly half a revolution apart, were bisected by the vertical wire, starting from each tenth of a revolution and taking each time the mean of five independent settings. This operation, comprising 200 settings, was performed three times.

Another interval of nearly one-fourth of a revolution was measured in the same way and as many times. All the $6 \times 200 = 1,200$ single settings were then treated by Bessel's method and resulted in the following formula for the correction ϕu to a given reading u of the micrometer head :

$$\phi u = +0.00045 \cos u \quad +0.00180 \sin u \quad -0.00151 \cos 2 u \quad +0.00071 \sin 2 u.$$

From this formula a table has been constructed, of which only that part is here given that will be actually used in our measurements.

2. Progressive Errors.—An interval of nearly five revolutions was measured from the starting points

$$0.0^{\text{R}}, \quad 5.0^{\text{R}}, \quad 10.0^{\text{R}}, \quad 15.0^{\text{R}}, \quad 20.0^{\text{R}}, \quad 25.0^{\text{R}},$$

each reading being the mean of five independent settings. This operation was performed five times, giving 300 settings.

Another interval of nearly the same size was measured from the starting points :

$$0.0^R, \quad 1.0^R, \quad 2.0^R, \quad \dots \quad 25.0^R,$$

each reading being again the mean of five independent ones. The whole set, therefore, comprises 260 readings.

A third interval, $m' - m = 3$ Rev. was measured from every third revolution in the same way, by 100 separate readings. The operation was then repeated twice, giving 300 readings.

From all these 860 micrometer readings the usual equations of condition were formed :

$$\text{Interval} = m' - m + fm' - fm = \text{etc.}$$

and the resulting corrections fm to given readings m were graphically adjusted.

As a standard revolution the *one-tenth part of the screw between the readings* 10.0^R and 20.0^R was chosen, which gives a convenient symmetry to the table of corrections. The table has been computed to four decimal places and all the numbers were rendered positive by the addition of $+0.0051^R$.

The *table* below gives 3 decimal places, the only ones that will actually be used in the measurements.

TABLE I.

Periodic Errors of the Micrometer Screw.

u	ϕu	u	ϕu
R			
0.00	—0.0011	1.00	—0.0011
0.01	—0.0008	0.99	—0.0012
0.02	—0.0005	0.98	—0.0014
0.03	—0.0003	0.97	—0.0015
0.04	—0.0001	0.96	—0.0017
0.05	+0.0002	0.95	—0.0018
0.06	+0.0004	0.94	—0.0018
0.07	+0.0007	0.93	—0.0018
0.08	+0.0010	0.92	—0.0018
0.09	+0.0013	0.91	—0.0019
0.10	+0.0016	0.90	—0.0018

TABLE II.

Progressive Errors of the Micrometer Screw.

m	$f\ m$	m	$f\ m$
R		R	
0.0	+0.026	30.0	+0.027
1.0	+0.024	29.0	+0.024
2.0	+0.021	28.0	+0.021
3.0	+0.018	27.0	+0.018
4.0	+0.016	26.0	+0.016
5.0	+0.013	25.0	+0.013
6.0	+0.011	24.0	+0.011
7.0	+0.009	23.0	+0.009
8.0	+0.007	22.0	+0.008
9.0	+0.005	21.0	+0.006
10.0	+0.004	20.0	+0.005
11.0	+0.002	19.0	+0.003
12.0	+0.001	18.0	+0.002
13.0	+0.000	17.0	+0.001
14.0	+0.000	16.0	+0.000
15.0	+0.000	15.0	+0.000

3. The *value of one revolution* of the micrometer screw will be determined *separately for each plate*. The following are some of the reasons :

(a) The focus of the microscope has to be changed for different observers, and may be changed by the same observer for different plates. Experiments for improving the actinic focus of the transit instrument will occasionally be made, and an arrangement is contemplated for separating the lenses of the objective.

(b) Errors arising from any possible change of distance between the glass reticule and sensitive plate are thus eliminated, and the inclination of the star trail to the vertical line of the reticule is of no consequence.

(c) If the sensitive plate be mounted in the transit instrument obliquely to the line of collima-

tion, the distance of the dots will appear enlarged, and the value of one revolution will accordingly be diminished.

The following *table* gives different values of one revolution, applying to plates already measured. The differences from the average value clearly show the effect of focus used by different observers or by the same observer for different plates.

TABLE III.

Values of the Micrometer Screw in the Order of \pm Declinations.

Plate.	δ	$\cos \delta$	1 Revol.	R. cos. δ	Resid.	Observer.
284	+14° 34'	0.9679	0. ^s 8932	0 ^s .8645	+0.0025	F.
226	—16 34	9585	0.9071	8695	— 25	F.
292	+20 16	9381	0.9220	8649	+ 21	F.
314	+21 4	9332	0.9415	8786	— 116	H.
283	+28 29	8790	0.9883	8786	— 116	H.
304	+31 33	8522	1.0150	8650	+ 20	F.
294	+34 28	8245	1.0268	8466	+ 204	F.
299	+40 32	7600	1.1416	8676	— 6	F.
310	+41 5	7538	1.1436	8620	+ 50	F.
293	+41 48	7455	1.1604	8650	+ 20	F.
316	+44 56	7079	1.2280	8693	— 23	F.
311	+45 53	6961	1.2458	8672	— 2	F.
303	+47 26	6764	1.2875	8709	— 39	F.
301	+49 28	6499	1.3316	8654	+ 16	F.
290	+59 40	5050	1.7189	8680	— 10	H.
288	+60 7	4982	1.7433	0.8685	— 15	H.

Mean = 0^s.8670

B.—THE METHOD OF MEASUREMENT.

1. The photographic *plate*, when mounted in the holder of the microscope, exhibits a horizontal series of dots, representing star places one second of time apart, and two portions of the vertical line of the reticule, the one above, the other below the star trail.

The latter is brought nearly to the horizontal thread of the micrometer, and the vertical

line of the plate to the vertical thread of the micrometer, which has previously been set at 15.0^{R} , and then, by means of the position-micrometer screw, both vertical lines are set exactly parallel. This operation is repeated until the adjustment is satisfactory.

2. The dots may be supposed equally distant from each other within the range of 30 revolutions of the screw, which equals 8 millimeters. For, the focal length of the transit instrument being 1.962 meters, the extreme dots are only 7 minutes of an arc from the middle, and hence their distances may be considered proportional to time.

However, for the sake of eliminating various kinds of errors and for convenience in computing, it has been made a rule to measure only *pairs of corresponding dots*, viz., such as are situated on opposite sides of the middle line and equally, or very nearly equally, distant from it, and to consider each pair as a single transit.

In fact, *distortions* of the film during development, or of the image in the microscope, seem to be effectually eliminated in this way.

Again, combinations by pairs always include *odd* and *even* seconds and give the star place invariably at the *half* second. Any inequality between odd and even seconds is thus thrown into the clock correction.

Finally, the mean of all the star places thus found is always *within a fraction of a second* of the middle wire, and consequently any uncertainty in the value of one revolution of the screw expressed in time is of little consequence in measuring so small an interval.

3. Another rule followed throughout consists in taking the *middle* of the dots as the beginning of each second. In this way we eliminate the errors by which the *diameter* of the star-image is changed, as for example, the magnitude, color, and declination of the star, changes in the atmospheric conditions and moonlight, the degree of sensitiveness in different plates or in different parts of the same plate.

An error of a periodic character is also eliminated by this method. The wheel on the axis of the second-hand in our sidereal clock, which breaks the electric current, is slightly *eccentric*, and the breaks are consequently of unequal duration, the longest being near the 40th second and the shortest near the 10th. In this way the breaks begin too soon in the one case and too late in the other, but the middle of the break remains free from this error.

This rule, however, might seem to introduce another error, arising from the weakening of the battery and the consequent prolongation of the breaks. For this reason Daniell-cells are always used, and a spare battery is constantly kept in readiness. Experience has shown that the ear, accustomed to the beating of the photochronograph, readily perceives the slightest change in the breaks.

For greater security the breaks have occasionally been tested on the chronograph, at different hours of the night, but no retardation has ever been detected. In fact, the battery being in use only about five times an hour, for two or three minutes at a time, it would seem to have ample time to recover its strength during the intervals.

4. The *actual measurements* are then made in the following manner. The wire of the micrometer is set five times on the vertical line of the plate, and the mean of the five readings (always about 15.0^R) written down. The wire is then brought back to revolution 0.0^R , and the dots available within 30 revolutions of the screw measured in the direction of increasing readings of the graduated head. The mean of 5 independent settings is taken as the place of a dot.

When the wire comes to revolution 15.0^R the vertical line of the plate is again measured 5 times, and a third measure is taken, after the last dot near revolution 30.0^R is completed.

A table of approximate intervals of the dots at different declinations serves as a guide in distinguishing faint or diffused dots from specks on the photographic film. Since an equatorial interval equals about 1.12 revolutions, more than 13 pairs of dots of an equatorial star cannot be measured.

The *time* corresponding to each dot is found by means of the pauses. The 29th, 57th, 58th, and 59th seconds do not break the circuit, and the star produces no image on the plate at these moments. Thus each minute has two pauses, which are visible simultaneously in the microscope and serve to check each other. Experience has shown that it would be more convenient to retain the 58th second.

According to the arbitrary but invariable manner in which our plates are mounted, both in the transit instrument and in the microscope, the time increases *with* the readings of the micrometer screw when the clamp of the transit instrument was on the *east* side, the opposite taking place for clamp west.

C.—THE METHOD OF REDUCTION.

1. The reduction we have adopted for the measurements thus obtained will be understood from the following example, referring to plate No. 226, represented above (Fig. 4) and belonging to the star *Sirius*.

TABLE IV.

*Specimen Plate.*Plate 226, *Sirius*, Clamp West.(a) *Wire:*

$$14^{\text{R}}.9948 - 0.0113, [v^2] = 0.00019659$$

$$9764 + 71$$

$$9792 + 43$$

$$14.9835 \pm 0^{\text{R}}.0038 = 0.6745 \sqrt{\frac{[v^2]}{2 \times 3}}$$

$$\phi = -14$$

$$14.9821$$

(b) *Pairs of Dots:*

t	m	f	ϕ	t'	m'	f	ϕ	m	m'	$\frac{1}{2}(m+m')$	v
48 ^s	^R 0.985	+0.024	—0.001	23 ^s	^R 28.539	+0.023	—0.002	^R 1.008	^R 28.560	^R 14.784	+31
47	2.196	21	+ 3	24	27.424	19	— 1	2.220	27.442	831	—16
46	3.293	18	+ 3	25	26.357	17	+ 1	3.314	26.375	844	—29
45	4.400	15	— 1	26	25.374	14	0	4.414	25.388	901	—86
44	5.451	12	— 2	27	24.310	12	+ 2	5.461	24.324	892	—77
43	6.538	10	— 2	28	23.108	9	+ 2	6.546	23.119	832	—17
41	8.651	6	— 1	30	20.826	6	— 1	8.656	20.831	743	+72
40	9.855	4	— 1	31	19.750	4	0	9.858	19.754	806	+ 9
39	10.991	2	— 1	32	18.554	3	— 2	10.992	18.555	773	+42
38	12.018	1	— 1	33	17.538	2	— 2	12.018	17.538	778	+37
37	13.159	0	+ 3	34	16.535	1	— 2	13.162	16.534	848	—33
36	14.147	0	+ 3	35	15.354	0	+ 1	14.150	15.355	753	+62

$$T = \frac{504}{12}$$

$$T' = \frac{348}{12}$$

$$M = 7.6499, M' = 21.9812; 14.8154$$

$$\frac{1}{2}(M + M') = 14.8155$$

(c) Mean of times = $\frac{1}{2}(t + t') = 35^{\text{s}}.5$, and

$$\text{mean place of star} = \frac{\text{R}}{14.8155}$$

$$\text{wire} = 14.9821$$

$$\text{Distance of star from wire} = \frac{\text{R}}{-0.1666}$$

$$= \frac{\text{S}}{-0.1510}.$$

Hence, *star on wire* at $35^{\text{s}}.349 \pm 0^{\text{s}}.009$.

(d) Value of one *Revolution* of the *Screw in Time* :

$$M' - M = 14^{\text{R}}.3313, \quad T' - T = \frac{156}{12} = 13^{\text{s}},$$

$$\text{hence, one revolution} = \frac{T' - T}{M' - M} = 0^{\text{s}}.9071.$$

(e) *Probable Errors* :

$$[v^2] = 0.029003, \text{ hence mean error : } \varepsilon = \sqrt{\frac{[v^2]}{11}} = \pm 0^{\text{R}}.0513.$$

The probable error of a *single pair* of dots, therefore = $q\varepsilon = \pm 0^{\text{R}}.0346$
 $= \pm 0^{\text{s}}.0313,$

and that of *twelve pairs* = $\frac{q\varepsilon}{\sqrt{12}} = \pm 0^{\text{s}}.009.$

2. The several parts of this reduction need some explanation.

The position of the *middle wire* in (a) has been corrected for the periodic error of the screw, the progressive error being always zero. Its probable error is so small, compared to that of a single pair of dots, that it can have no influence on that of the relative distance between the mean of the pairs and the wire, since, in this case, we would have [see (e)] :

$$\sqrt{r^2 + r'^2} = r \sqrt{1.01} = 1.005 \times r$$

or equal to r within a few units in the fourth decimal place.

In the table (b) the letters t and m denote *time* and *micrometer reading* respectively for the single dots, the accents referring to “corresponding” dots and the capital letters to the *arithmetical means* ; the letters f and ϕ denote, as in section A, the *errors of the screw*, progressive and periodic, and the letter v the *residuals* from the mean. This mean has been computed in two ways expressed by the formula

$$\frac{1}{n} \sum \frac{1}{2} (m + m') = \frac{1}{2} (M + M'),$$

where n is the number of corresponding pairs.

The periodic errors ϕ are small and nearly compensate each other, as was to be expected. Besides, compared with the probable error of the result, they have practically no meaning, and shall, therefore, in the future be discarded. Their application to the middle wire, however, will be retained as it effects the distances of all the dots in the same way. For this purpose the abridged form of Table I will be amply sufficient.

The figures given in (c) will be understood from (d) and (e).

The *value of one revolution* of the screw in (d) has been computed from the following pro-

portion, in which x is the unknown number of seconds corresponding to one revolution of the screw :

$$\frac{x}{1} = \frac{t' - t}{m' - m} = \frac{t'_1 - t_1}{m'_1 - m_1} = \text{etc.}$$

This proposition admits of two solutions :

$$x = \frac{\Sigma (t' - t)}{\Sigma (m' - m)} = \frac{T' - T}{M' - M}, \text{ and } x = \frac{1}{n} \Sigma \frac{t' - t}{m' - m},$$

which, theoretically, should indeed be identical, but usually differ from each other on account of the errors of the single fractions.

Which of the two gives more reliable results, will appear from the following comparisons :

$t' - t$	$m' - m$	x	v
25 ^s	27.552 ^R	0 ^s .9074	— 5
23	25.222	9119	— 50
21	23.061	9106	— 37
19	20.974	9059	+ 10
17	18.863	9012	+ 57
15	16.573	9051	+ 18
11	12.175	9035	+ 34
9	9.896	9095	— 26
7	7.563	9255	
5	5.520	9058	
3	3.372	8897	
1	1.205	0.8300	

$$\frac{1}{8} \Sigma \frac{t' - t}{m' - m} = 0^s.9069.$$

The first 8 intervals give nearly the same result 0^s.9069 as the formula

$$x = \frac{T' - T}{M' - M} = 0^s.9071, [\text{Table IV. (d)}],$$

whilst the smaller intervals introduce large errors, as was to be expected. For this reason the latter formula will be exclusively used.

The residuals v of the first 8 intervals afford an approximate idea of the error of x . We find :

$$[v^2] = 0^s.00009399 \text{ and } 0.6745 \sqrt{\frac{[v^2]}{8 \times 7}} = \pm 0^s.0009.$$

This error, being only one-tenth of that of the final star place, may be discarded when the latter is computed.

For the several reasons mentioned, the *probable error* of the star place in (e) has been computed simply from the residuals v of the quantities $\frac{1}{2}(m + m')$.

D.—SPECIMEN SET OF TRANSITS.

Out of the five first complete sets of transits that we obtained last December, the one of December 13th has been *chosen at random* for first computation. In this set 15 plates were found intense enough for measurement, and none of these were subsequently rejected, so that the results given are quite the average ones.

Greater accuracy may, however, be expected in the future from longer experience in the line of precautions that this method requires, from modifications of the microscope and from improvements of the actinic focus.

1. It will not be necessary to give here the measures and reductions of the single plates, as in the above example of *Sirius*, and a *general summary* will suffice.

TABLE V.

General Summary of Measures in the Order of Right Ascensions, December 13, 1890.

Plate.	Star.	Measures.	Probable Error of		Number of Pairs.
			Single Pairs.	Means.	
		Clamp	East.		
283	α Andromedae .	56. ^s 787	± 0.030	± 0.009	12
284	γ Pegasi . . .	49.254	0.030	0.009	11
288	γ Cassiopejæ .	18.661	0.090	0.033	7
290	δ Cassiopejæ .	52.198	0.049	0.015	10
292	β Arietis . . .	49.468	0.059	0.021	8
293	γ Andromedae .	24.454	0.053	0.015	13
294	β Trianguli . .	15.479	0.029	0.013	5
		Clamp	West.		
299	β Persei . . .	19.535	0.059	0.016	13
301	α Persei . . .	47.824	0.072	0.019	14
303	δ Persei . . .	25.122	0.056	0.015	14
304	ζ Persei . . .	31.806	0.071	0.019	14
310	η Aurigæ . . .	7.516	0.049	0.014	12
311	α Aurigæ . . .	53.759	0.046	0.011	16
314	ζ Tauri . . .	22.925	0.018	0.007	7
316	β Aurigæ . . .	47.483	0.039	0.010	15

2. In order to find a *law for the probable errors* of the single pairs of dots, as far as the scanty material will allow, we will arrange the plates in the order of declinations and compare the errors, expressed in revolutions of the screw, with a scale of definition or intensity of the plates, with the magnitudes and colors of the stars (taken from the Harvard Photometry), and with the increase of declination.

TABLE VI.

Probable Errors of the Single Pairs in Revolution and Time in the Order of Declinations.

Plate.		Star.		Probable errors in revolutions.		Probable errors in time.		
No.	Scale.	Mag.	Color.	Of single pairs.	Resid.	Formula.	Direct.	F. — D.
284	Very good.	2.6	—	$\pm 0.034^R$	$+ 0.004^R$	$\pm 0^s.034$	$\pm 0^s.030$	$+ 0^s.004$
226	Excellent .	Sirius.	W	34	+ 4	34	31	+ 3
[292]	Tolerable .	2.8	W	[64]	— 26	35	[59]	— [24]
314	Good . .	3.3	W	19	+ 19	35	18	+ 17
283	Very good.	2.0	W	30	+ 8	37	30	+ 7
[304]	Tolerable .	3.0	y	[61]	— 23	39	[71]	— [32]
294	Good . .	3.0	y	29	+ 9	40	29	+ 11
299	Good . .	2.5	W	51	— 13	43	59	— 16
310	Good . .	3.6	W	43	— 5	44	49	— 5
293	Tolerable .	2.4	y	46	— 6	44	53	— 9
316	Very good.	2.0	W	32	+ 6	47	39	+ 8
311	Excellent .	1.0	w	37	+ 1	47	46	+ 1
303	Good . .	3.1	W	44	— 6	49	56	— 7
301	Good . .	2.0	W	54	— 16	51	72	— 21
290	Good . .	2.8	W	28	+ 10	65	49	+ 16
288	Tolerable .	2.8	W	0.052	— 14	0.066	0.090	— 24

Average = $\pm 0.0381^R$

The errors expressed in revolutions do not seem to follow the order of declinations, nor is there any apparent connection between them and the magnitudes and colors of the stars, whilst, on the other hand, their dependency on the “scale” of the plates is quite evident. In particular, the two large errors in parenthesis are due to the very poor definition of the dots. If these two plates are left out, the *average probable error of a single pair of dots*, or, as we have called it (above B, 2.), of a single transit, is:

expressed in *revolutions* = $\pm 0^R.0381$, or (see Table III.)

expressed in *time* = $\pm 0.0381 \times 0.8670 \text{ sec } \delta = \pm 0^s.033 \text{ sec } \delta$.

Taking the two plates discarded into account we should have $\pm 0^s.0356 \text{ sec } \delta$.

The last three columns of the above table give the probable errors of single pairs expressed in time, in two ways, the first computed from this formula, and then directly from the general summary (Table V).

The fact that the formula differs in shape from the one given by Prof. Albrecht (Formeln u. Hilfstafeln, Leipzig, 1873, p. 7):

$$\sqrt{0.07^2 + \left(\frac{3.18}{v}\right)^2 \sec^2 \delta} \text{ for the eye and ear method}$$

$$\sqrt{0.05^2 + \left(\frac{3.18}{v}\right)^2 \sec^2 \delta} \text{ " " chronographic " "}$$

in which v denotes the magnifying power, can not be surprising, since the upper represents errors of a partly different nature, and, in particular, excludes all the errors arising from the so-called "personal equation," from the difference between north and south stars, between lower and upper culmination, and generally from the position of the observer's head.

The term $c \sec \delta$, common to all methods, seems in the main attributable to a disturbance usually called unsteadiness of the atmosphere. Its influence on the star-image, seen in its flaring, quivering, and dancing in every direction, so well known to observers, is reproduced with great fidelity by the sensitive plate. For, on certain nights, the star trails show slight deviations from a straight line, the dots being somewhat displaced in every direction.

The probable error $\pm 0.033 \sec \delta$ is therefore due mainly to the horizontal displacement or *lateral refraction*, which can not be eliminated, however refined the method.

In confirmation, it may be stated that the probable error of a single bisection and micrometer reading with regard to the *same* dot was found to be, on the average, only $\pm 0.006^R$, or for a pair of corresponding dots,

$$\pm 0.0085^R = \pm 0^s.007 \sec \delta,$$

a quantity less than one-fourth of the whole error.

3. The *instrumental constants* have been determined as follows:

(a) The value of one division of the *hanging level* is

$$1^p = 0^s.0751 \pm 0.0003$$

as determined from 25 intervals, measured by means of the micrometer and a collimator.

The *inequality of the pivots* was determined by 5 independent sets of level readings, each set containing 10 readings for each position of the clamp, and was found

$$= +0^s.009 = +0.''135,$$

which quantity is to be added to the readings of the level for clamp west and to be subtracted for clamp east.

The pivots may be supposed of *circular* shape, since they were turned off when the instrument was repaired shortly before these observations began.

The *level constant* b on December 13th was found as follows :

	Sidereal time.	b
Clamp east	$\begin{matrix} \text{h.} & \text{m.} \\ 0 & 0 \end{matrix}$	$= +0^s .111$
	$\begin{matrix} 2 & 18 \end{matrix}$	$= +0 .147$
Clamp west	$\begin{matrix} 2 & 22 \end{matrix}$	$= +0 .170$
	$\begin{matrix} 4 & 15 \end{matrix}$	$= +0 .045$
	$\begin{matrix} \text{h} \\ 6 \end{matrix}$	$= -0 .257$

The last reading, at the close of the evening's work, must be erroneous, as it agrees neither with the star places nor with a graphical representation. Our level is not protected by a glass casing and proves very sensitive to changes of temperature. Experiments made for the purpose have shown that the bubble is not affected by the reading lantern, as might be feared, but may be made to run in any direction by the action of the breath of the observer on the glass tube. The last reading has therefore been replaced by a graphical extrapolation from the preceding ones.

(*b*) The *azimuth* and *collimation* constants had to be determined from the transits themselves and comparison with the known star places, for reasons explained in the first part. The following table represents the most probable values of the constants with the corresponding corrections:

RESULTS OF THE PHOTOGRAPHIC TRANSITS.

TABLE VII.

Correction for Instrumental Errors:

$$a A + b B + c C.$$

Azimuth constant: $a = -0.^s29$ for clamp east.

$a' = -0.15$ “ “ west.

Collimation constant: $c = +1.^s01$.

Plate.	$a A$	$b B$	$c C$	Sum.
283	$-0.^s060$	$+0.^s123$	$+1.^s149$	$+1.^s212$
284	-0.124	$+0.104$	$+1.044$	$+1.024$
288	$+0.209$	$+0.232$	$+2.026$	$+2.467$
290	$+0.204$	$+0.250$	$+1.998$	$+2.452$
292	-0.098	$+0.152$	$+1.073$	$+1.127$
293	$+0.018$	$+0.201$	$+1.355$	$+1.574$
294	-0.027	$+0.181$	$+1.226$	$+1.380$
	$a' A$	$b B$	$c C$	
299	$+0.005$	$+0.158$	-1.329	-1.166
301	$+0.042$	$+0.151$	-1.553	-1.360
303	$+0.033$	$+0.117$	-1.493	-1.343
304	-0.023	$+0.070$	-1.186	-1.139
310	$+0.008$	$+0.026$	-1.341	-1.307
311	$+0.026$	$+0.028$	-1.450	-1.396
314	-0.049	$+0.010$	-1.083	-1.122
316	$+0.022$	$+0.000$	-1.426	-1.404

(c) The *clock correction*, as computed from *all* the 15 stars, was found to be

$$\Delta T = -13^s.912.$$

Comparing, then, the resulting star places with those of the *Berlin Jahrbuch*, there is no indication of a *clock rate*. That the hourly rate may, in the course of the evening, have reached zero, is indeed very probable from a comparison with the rates of the preceding days, its

average for the last 33 hours having been less than one-half of what it had been during the two weeks preceding, from noon to noon.

4. We give, in the following table, the resulting *Right Ascensions* of the 15 stars, with the places interpolated for our meridian on December 13 from the Berlin Jahrbuch, and the differences of both lists, in the sense: Photographs—Berlin Jahrbuch.

TABLE VIII.

Resulting Right Ascensions, December 13, 1890.

Plate.	No. of Fund. Cat.	R. A. from Photogr.			B. J.	Ph. — B. J.
		h.	m.	^s	^s	^s
283	1	0	2	44.09	44.15	—0.06
284	3	0	7	36.37	36.37	0.00
288	13	0	50	7.22	7.17	+0.05
290	20	1	18	40.74	40.76	—0.02
292	30	1	48	36.68	36.59	+0.09
293	32	1	57	12.12	12.08	+0.04
294	34	2	3	2.95	3.05	—0.10
299	50	3	1	4.46	4.41	+0.05
301	52	3	16	32.55	32.48	+0.07
303	57	3	35	9.87	9.88	—0.01
304	63	3	47	16.75	16.75	0.00
310	83	4	58	52.30	52.40	—0.10
311	86	5	8	38.45	38.43	+0.02
314	98	5	31	7.89	7.89	0.00
316	103	5	51	32.17	32.21	—0.04

If we consider these residuals as the errors in the determination of the clock correction $\Delta T = -13^s.912$, the *probable error* of the latter is

$$0.6745 \sqrt{\frac{0.0147}{15 \times 14}} = \pm 0^s.0099.$$

5. In *conclusion* the following remarks may serve to estimate the bearing of the results.

While the probable errors of a single pair of dots in the measurement of the plates, or of

the resulting clock correction, and the residuals of the star places, may perhaps appear a little smaller than in the usual methods, it is not so much these smaller figures that seem to promise for this method a practical importance as the *entire absence of the personal equation*.

A photographic transit is, on the whole, more laborious than one taken by the chronograph, yet it certainly makes it possible for us to eliminate the personal equation in all cases where such elimination must be purchased at any cost.

As an example, we need only mention *longitude* determinations. The usual exchange of the observers, so expensive in time and money, is, by the photographic method, rendered unnecessary and even useless. If the photochronographs at the two stations are worked by the same clock at either station, or at an intermediate one, the sensitive plates will record the difference of the two meridians without the interference of the observers.

The photographing of star transits will be continued at this Observatory for all the stars within the reach of our equipment, in order to study the nature of the peculiar errors of this method, and to test its efficiency in regular zone work.

CORRIGENDA.

Page 12, line 29, *for* "blackened" *read* "whitish."

Page 12, line 30, *for* "white" *read* "black."

Page 15, line 25, *for* "answer" *read* "answers."

Page 25, line 29, Plate No. 226 was accidentally broken during the process of reproduction, and Figure 4 is taken from Plate No. 407, which is the transit of Sirius for January 29th, 1891.

Page 25, line 29, *for* "above" *read* "below."

Page 28, line 4, *for* "proposition" *read* "proportion."

GEORGETOWN COLLEGE OBSERVATORY.

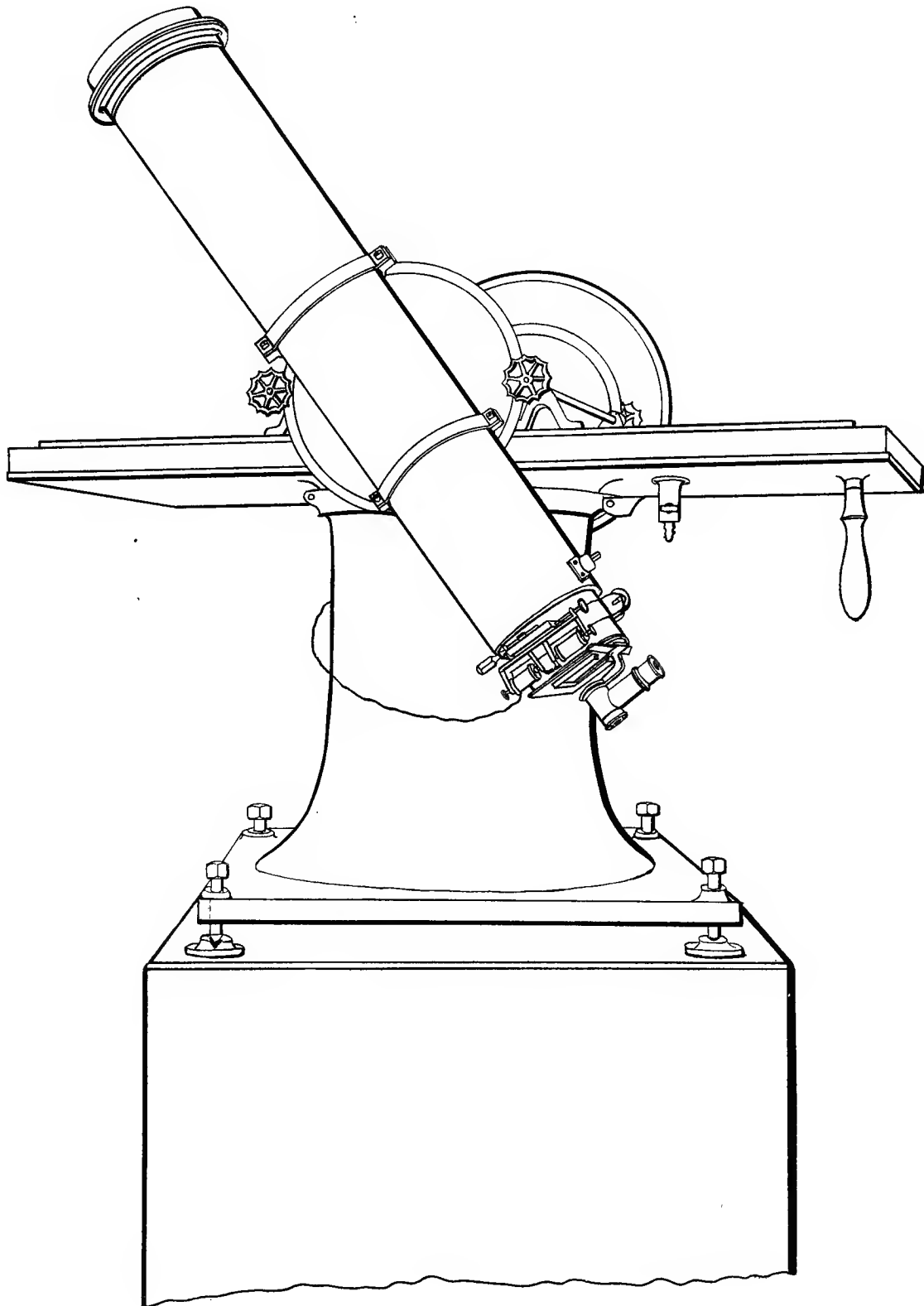
THE PHOTOCRONOGRAPH

APPLIED TO

DETERMINATIONS OF LATITUDE.

STORMONT & JACKSON,
PRINTERS,
WASHINGTON, D. C.
1892.

THE FLOATING ZENITH TELESCOPE



PREFACE.

The determination of latitudes, and in particular of their periodic variations, by means of photography has repeatedly been pronounced feasible and highly desirable, *e. g.*, in the *Astronomische Nachrichten* (No. 2982, page 81, and No. 3015, page 241), yet a practical method which would afford all the advantages of the usual methods and, at the same time, put the whole record graphically on a sensitive plate, has never been suggested.

The problem has been kept in mind at this Observatory for several years back, and it was a settled conclusion from the beginning, that the spirit-level should be replaced by mercury. Two ways of doing so were open, which may be called the *reflecting* and the *floating* principles. Neither of them is new. The former is in constant use in connection with the meridian circle, and forms an essential part of Airy's Reflex Zenith Tube (Greenwich Observations in the year 1854, Appendix I), the latter has been applied, for the first time it would seem, by Captain Kater in his floating collimators (Phil. Trans. 1825, p. 153, and 1828, p. 257), and recently by Dr. Chandler in his Almucantar (Annals of Harvard College Observatory, Vol. XVII., 1887.)

Early in 1891 the plan was so far advanced that the floating principle was adopted. Yet it remained incomplete, until Professor G. A. Fargis, S. J., suggested the application of the Photochronograph.

In the first week of August, 1891, the order was given for the new instrument. Its construction was not entrusted to one of the known instrument makers, as the advisability of subsequent changes, arising from experience, was foreseen. The portability of the instrument did not enter the plan proposed, and no attempts were made to secure lightness or gracefulness of make.

Two parts of the instrument, however, had to be perfect from the beginning, the objective and the Photochronograph. The former was procured from Mr. Brashear, and possesses undoubted excellence ; the latter was made by Mr. Saegmuller, and is a finished piece of workmanship.

The Photochronograph used in latitude work differs in several respects from the one used in transit work. Both are the entire invention of Prof. Fargis.

It will not be too much to say, then, that the Photochronograph, in its various shapes, has succeeded in solving the double problem of determining, by way of photography, the two coördinates of observatories : *Longitude* and *Latitude*.

It affords us great pleasure to return our heartfelt thanks to Mrs. Maria Coleman, who has furnished the means for constructing this instrument and providing a suitable building.

Alumni and friends of the College will be glad to hear, that this donation was due to the kind offices of the former President, Rev. P. F. Healy, whom the Observatory will ever hold in grateful remembrance.

J. G. HAGEN, S. J.

GEORGETOWN COLLEGE, May, 1892.

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THE PHOTOCRONOGRAPH

APPLIED TO

DETERMINATIONS OF LATITUDE.

By GEO. A. FARGIS, S. J.

PART I.

DESCRIPTION OF THE INSTRUMENT.

The general appearance of the instrument may be gathered from Plate III. It consists essentially of a photographic telescope attached to a float placed in mercury. The most novel part of the instrument is the construction of the eye-end, as will appear from the detailed description which follows.

1. The *pier* is composed of concrete. It rests on a bed of compact gravel, and starts with a cube measuring 5 feet each way. Above this it rises in the form of a pillar, 3 feet square at the base and 4 feet high. On top of the pier stands an *iron support*, 2 feet square at the foot and 21 inches high. The base is provided with four levelling screws. The upper part terminates in a *narrow ring*, 15 inches in diameter and half an inch in width. A strong *vertical axis*, fastened to the bottom of the trough, passes through the hollow iron support and rests in a screw at the base of the latter, by means of which the whole superstructure can be partially lifted from the turn-circle for the purpose of diminishing friction. There is no horizontal graduated circle for position in azimuth, as the instrument is used only in the meridian. It has, however, two *stops*, with adjusting screws, placed north and south, which answer the purpose. The various electrical connections for the photochronograph and incandescent lighting, are made by means of flexible wires, passing through openings made in the iron support.

On the turn-circle rests the *trough* containing the mercury. It consists of a cast-iron plate about 46x16 inches and is about three-quarters of an inch thick, strengthened on the under side by radiating ribs. A band of wrought-iron $1\frac{3}{4}$ inches wide is fastened to the sides, thus forming a shallow trough. It was found impossible to cast the base and sides in one piece, on account of the distortion due to unequal cooling. The inner surface of the trough was in con-

sequence covered with cement, to make it mercury-tight and level. The surface of the cement was purposely suffered to remain rough. For this, it was thought, would serve to check any undue oscillation of the mercury, whilst not interfering with the buoyancy of the float, on which alone, as it would seem, the sensitiveness of the instrument depends.

This idea was suggested by M. D'Abbadie, who in his experiments on the variations of "The Vertical," at Abbadia, near Hendaye (Basses-Pyrénées), between the years 1867 and 1881, employed corrugated mercury basins, with grooves 7 millimeters deep, and he mentions that Leverrier had previously availed himself of a similar device in the much disturbed Paris Observatory.*

The trough is furnished with a *faucet* at either end, for drawing off or regulating the quantity of mercury, of which there is about fifty pounds. It also carries a pair of *adjustable Y's* on the east and the west side, which can be raised or lowered vertically, and serve a very important purpose, to be described in connection with the float.

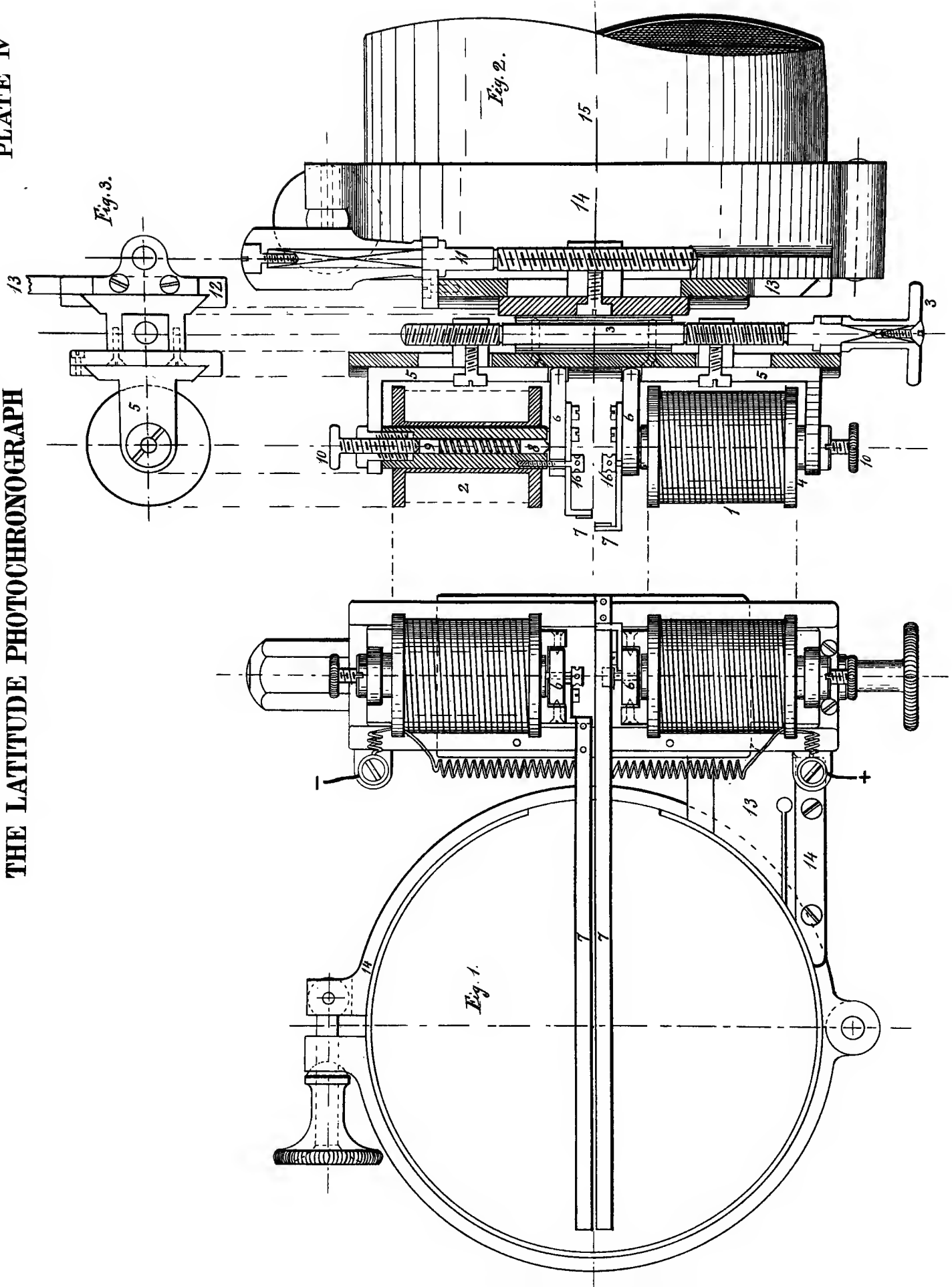
2. The *float* is a rectangle 15x45 inches, and about an inch thick. It is of wood in an iron frame. The under surface is coated with a mixture of varnish and sand, designed to present a rough surface to the mercury for the reason just given. It is provided with a pair of *Y's* for the axis of the telescope. It has also an iron bar, parallel to this axis, projecting over the outer edge of the trough, carrying a pair of *knife edges* of hardened steel. These knife edges fit into the adjustable *Y's* on the trough, and by their means the float with the telescope may be lifted a trifle from the mercury, so as to secure its position in azimuth without interfering with its free motion in the meridian. For, as experience shows, its sensibility in this direction is still extreme.

These knife edges constitute an essential difference between this instrument and that of Captain Kater, who "prevented" his own "from turning horizontally, by two smooth iron pins passing through the sides of the box into the grooves" (Phil. Trans., 1825, p. 153): His telescope was, consequently, exposed to oscillations from east to west, which, in the present instance, are excluded.

3. In the *Y's* on the float rests the *axis*, which carries the telescope and counterpoise. It is a cast-iron tube $2\frac{1}{4}$ inches in diameter, with a *clamp circle* at either end. These circles are iron discs, about a foot in diameter and $\frac{1}{2}$ inch thick. Bearing on their outer surfaces are two *clamps* for each circle. These clamps have their supports on the float, and in this way a rigid connection can be secured between the float and the telescope. On one end of the axis,

*Etudes sur la Vorticale, par M. D'Abbadie, Association Française pour l'Avancement des Sciences, Congrès de Bordeaux 1872; separate publication, page 6.

THE LATITUDE PHOTOCHRONOGRAPH



just outside the clamp circle, is a heavy *finding circle*, which serves partially as a counterpoise to the telescope. It reads directly to 5 minutes of arc, and can be set quickly to single minutes without verniers. Just outside this circle, on the end of the axis, left long designedly, is a movable weight, which serves to balance the instrument accurately before the float is raised by the adjustable **Y**'s.

4. On the other end of the axis, rigidly attached to the clamp circle by brass bands, is the *photographic telescope*. The *objective*, a single combination of two lenses, corrected for photographic rays, is 6 inches in diameter, with a focal length of 36 inches. This focal length was chosen to secure greater intensity of the image, so as to reach stars of at least 6.5 photographic magnitude. It has been found free from selective absorption, from veils, and from double refraction. The polish is excellent, and the focal image well defined. It readily gives trails of stars below the 7th photographic magnitude.

The *draw-tube*, 5 inches in diameter, has a rack-motion and clamp, and bears a *scale* graduated to millimeters. It terminates in a *rectangular brass plate* 5x6 inches, with an opening 2x4 inches. It has no wires of any kind. A light brass *frame-work* is placed in front of this opening in such fashion that the sensitive plate, when inserted, is about in the middle of the eye-end. The sensitive plate slips easily into position, and is held there firmly by flat springs. There is also a *diagonal eye-piece* arranged to slide back and forth to any part of the opening, and far enough away to allow of an easy insertion of the plate.

5. Just inside the brass plate is the *photochronograph*, attached to the draw-tube. Some modification of the form described on page 11 proved necessary, in order to adapt it to the present purpose, and it eventually took shape as it appears in Plate IV. The drawing is to scale, except that the draw-tube is actually one-fourth larger. Fig. 1 is the front elevation as seen from the eye-end of the telescope, looking forward in the direction of the object-glass; Fig. 2 is the side elevation, partly a section, and Fig. 3 is the ground plan of the sliding motions.

The photochronograph, used for latitude work, consists of two simple photochronographs symmetrically placed. [Pl. IV., Fig. 1.] One of the occulting-bars is placed a little behind the other, so as to permit them to overlap without touching, when the current is made, thus completely cutting off the stars from the sensitive plate.

The electro-magnets carrying the armatures, to which the occulting-bars are attached, can be made to approach or recede from each other by means of the right and left screw, 3 (Fig. 2). The range of motion is about half an inch. This enables the observer to separate the occulting-bars far enough to take in pairs, 15' or more, apart. The electro-magnets are

bi-polar, the soft iron cores, 4, being secured to the prismatic angle irons, 5. To the other extremities of these angles are attached the armatures, 6, which turn in pointed screws. At the core-ends these armatures are slotted, to allow the free play of the regulating screws, 16. These same screws, 16, as must be evident, control the range of the occulting-bars, 7. The soft iron cores are pierced, to make room for spiral springs of German silver. Each of these springs lies between two small sliding cylinders, 8 and 9, also of German silver. The tension of these springs is regulated by the screws, 10, according to the strength of the current. This arrangement serves the purpose of the spring commonly used on relays, as in the transit photo-chronograph [Pl. I., Fig. 1,], but it is more ingenious than satisfactory, and does not always behave as well as its nice construction promised.

By means of the screw, 11, the whole system may be moved vertically about one inch. Attached to the sliding-bar, 12, of this vertical motion is a dove-tailed arm, 13, which slides into the clamp-ring, 14, and permits the easy insertion or removal of the photochronograph, without disturbing the latter. The clamp-ring is secured to the draw-tube by a suitable screw-bolt. There are, of course, the usual connecting screws for the battery-wires, which pass through an opening in the iron base, to binding screws at the foot of the pier, thence under the floor to a switch at the writing-table, and thence to the clock-relay and batteries. A $\frac{1}{2}$ -candle incandescent lamp serves to light up the finding circle, as occasion requires.

6. Before proceeding to discuss the method of observation it may not be out of place to say a word about the *building* which shelters the instrument. It is a separate frame structure, 12x14x18 feet, on the east side of the Observatory, but connected with the main buildings by a short passage-way, which is, of course, always kept closed during the observations. Overhead is a rectangular box-shaped opening, the top of which projects beyond the gable of the roof, in order to protect the photographic work when the moon is near its full. For the same reason the two *shutters* on the opening stand upright to the east and west, and extend the whole length from north to south. They are counterpoised on the outside and open readily of themselves, when the ropes inside are loosened. The opening is 5 feet wide from east to west, and allows the instrument a sweep of 30° north and south of the zenith. For the better protection of the sensitive plate, the interior of the room is stained a dark neutral tint.

PART II.

ADJUSTMENT OF THE INSTRUMENT.

1. The *adjustments* of the instrument are extremely simple. The *focus* of the photographic telescope was readily determined by the method already described on page 15. It was found to be at 8 mm. of the scale on the draw-tube, which was then firmly clamped at that place, and the clamp-key removed. No fine adjustment for *collimation* is needed, as there are no wires at the eye-end. The *azimuth stops* on the north and south side of the iron base were so adjusted by means of adjusting screws, that the image of a star on the meridian is near the middle of the sensitive plate. This done, the photochronographic trail affords means of making a much finer adjustment. For as it exhibits the dots indicating the exact second of the meridian passage of either star of the pair, the adjustment is continued by means of the screws on the azimuth stops until the dots of the meridian passage of the north and south star are in the same vertical line. The manner of determining the exact moment of the meridian passage will appear from what follows.

The *levelling* of the instrument was done in the following way. First, the trough was levelled very readily by means of the mercury it contained, the depth at either end and at the sides being plainly visible, and the four screws at the foot of the iron pillar giving all the range needed. The float was then levelled, taking care that the knife edges did not bear on their **Y**'s, so that they might encounter equal pressure when the **Y**'s were raised. This was done by means of a striding-level placed on the horizontal axis, which carries the telescope and circle, and of the movable weight on the same axis. (See Part I, No. 3.)

Then the adjustable **Y**'s on the trough were raised until they held firmly the knife-edges of the float, the instrument was turned around on its vertical axis and the adjustments repeated, until the axis was found level for all positions.

This levelling is the principal part of the adjustment, because it secures the parallelism of the two star-trails, or rather of their tangents at the meridian passage. A plate on which this parallelism is not perfect is peremptorily rejected.

2. The operation of *setting* the instrument so as to obtain the photochronographic trails of the selected pairs of stars is performed thus. As the vertical circle reads from 0° to 90° in both directions from the zenith, the index has been adjusted so that its reading corresponds to the horizontal line formed by the meeting of the two occulting-bars of the photochronograph (Pl. IV, Fig. 1). Hence, when the circle is set on the mean zenith-distance of a pair of stars,

the two components will be equidistant from this line, and each star will be behind one of the occulting-bars. For pairs less than eight minutes of arc apart, the occulting-bars are allowed to overlap, when the current is broken, since their range is wide enough to give the pair room to affect the sensitive plate. For wider pairs the bars are separated by means of screw 3. The bars serve to protect the available portion of the plate from the intrusion of other stars and the moonlight.

The instrument once in position, and the bars adjusted for range, the first star of the pair is observed, by means of the diagonal eye-piece, and adjusted to the occulting-bar, as in the case of the photographic transit (see page 17). This, of course, insures the adjustment of the second star under the occulting-bar, when the instrument is reversed, and this is the reason for the two occulting-bars, for even if there were no other obstacle, the sensitive plate in the holder would prevent any observation of the second star. After this adjustment, the plate is inserted.

3. The *sensitive plates* are similar to those used in the transit observations. They are $1\frac{1}{2}$ by $2\frac{1}{2}$ inches, and are the "C" plates of G. Cramer, of St. Louis. There is no plate-holder, and the naked plate is slipped into the simple arrangement spoken of in the first part. The plate can be inserted only on one side, and projects about a quarter of an inch. Care is taken that this projecting end should be the numbered one, so that if the telescope is on the east side of the pier, the number will be on the south side of the plate, and will serve as a guide in the subsequent measurement.

4. The plate once in position, the instrument is left to itself. Stars will begin to imprint their trails on various parts of the plate, save, as has been said, on the portion protected by the occulting-bars. The observer, in the meantime, is seated at his desk, in front of a pendulum clock, previously adjusted to the second with the standard clock. Just at hand, on the wall, is a single point *switch* in the clock and photochronograph circuit, which gives him perfect control of the action of the pair of stars on the sensitive film. About half a minute before the meridian passage of the first star the switch is closed, the circuit is made, and the occulting-bars separate, exposing the plate to the action of the star. But the clock at once breaks the circuit, and the bars return to their original position, cutting off the rays of the star, and by this alternate making and breaking the circuit, and, in consequence, opening and closing the occulting-bars, a series of dots is imprinted on the plate. About half a minute after the meridian passage the switch is opened, the bars come together, and the first star has done its work. The half minute or minute at which the switch is opened and shut is noted down, and

serves afterwards in identifying the dot representing the meridian passage. The instrument is then immediately *reversed*, to give it time to come to rest before the next star is due. The same operation with the switch is repeated with the star, after which the plate is removed and the instrument adjusted for the next pair.

5. It will now be in order to say a few words about the *breaks* in the electric current, made by the clock just mentioned. It is evident that the breaks used in the photographic transit work carried on at this Observatory (see page 12) could not be used for the latitude instrument. First, because the focal length of the lens is so short that the dots would come too close together to be readily identified, and, again, an exposure of one-tenth of a second is generally too short for stars of 6.5 photographic magnitude. An adjustment was, therefore, devised which breaks the circuit at the even seconds only, for the space of one whole second. The developed plate then exhibits a line of dashes or dots separated by blank spaces of the same length. For one minute there would be 30 dots were it not for the pauses introduced to mark the beginning and end of the minute.

The beginning of the minute is indicated by cutting out three breaks and the middle by cutting out one. This cutting out is done automatically by the Gardner spring-contact, in a hack-clock. This hack-clock is directly connected with the relay of the standard-clock used for photographic transit work. By the simultaneous operation of these clocks various combinations of breaks are readily obtained. This arrangement was designed for photographic transit work, and by it the transits of northern stars, upper and lower culminations, and even of Polaris, have been successfully photographed.

It will be readily understood from what has been said that the star acts on the plate only when the circuit is made, and that at each break the star is occulted. When, then, there is a pause in the breaks the star makes a continuous trail. Consequently the plate shows at the beginning of each minute a dash or dot 9 seconds long and at the middle another of 5 seconds. These pauses are of the first importance for securing the identification of the dot representing the meridian passage. For stars of the fourth magnitude and brighter, where the full second exposure gives too broad a trail, the one-tenth second exposure is used with advantage.

Moreover, by means of a special switch, the break-circuit can be changed at will into a make-circuit. In this way the action of the occulting-bar is reversed, and the pauses, which appear as long dashes for faint stars, can be turned into blank spaces for the brighter ones.

PART III.

RESULTS FROM THE INSTRUMENT.

1. After the instrument had been adjusted as described, it was tested for *stability* and *sensitiveness* for the first time April 26th, 1892. The method fixed on was the following. Immediately after adjusting the star under the occulting-bar, and inserting the sensitive plate, the switch was turned on. The same was done promptly on reversing the instrument. In each case the star was allowed to trace its diurnal motion on the plate for an interval varying between 5 and 10 minutes. In this way the oscillations of the instrument in the direction north and south were photographed directly. Further still, since the range of the occulting-bars was wider than the amplitude of the wave of oscillation, the undulating trail left by the star was cut up into dots and blank spaces under the action of the photochronograph. When the plate was put under the microscope the observer had before him a faithful record of the elements of oscillation, the duration of the disturbance, the amplitude of the wave, and the time of the single oscillations.

The oscillations proved to be perfectly *synchronous* for all amplitudes. The cause of the disturbance, viz., the insertion of the plate, the reversal of the instrument, or strong gusts of wind, seemed to have no effect on the character of the waves; in all cases they remained the same.

Some of the plates showed as many as 10 waves, forming a serpentine trail of dots. It was found on inspection that 10 of these waves contained exactly 50 dots, and each wave, large or small, 5 dots, which gave 10 seconds as the time of one full oscillation. Similar results were obtained from all the plates without exception. As far as could be seen directly, the disturbance lasted for almost two minutes, but the micrometer screw detected it for some time longer. The largest amplitudes, starting from the position of equilibrium, ranged between 20 and 58 seconds of arc. They gradually decreased, seemed to disappear, and the trail apparently became straight. Still, attempts to determine latitude by actual measurements of these trails, showed that the disturbance had not ceased with the disappearance of the wave, as the determinations deviated at their widest by as much as 10 seconds of arc.

The practical conclusions drawn from these experiments were, that the instrument needed at least three minutes' rest before a star could produce a trail fit for the micrometer, and that a

strong wind introduces considerable uncertainty in the measurements. Some, if not all, of the bad effects of the wind on the float are avoided by the use of a light shield, which has been attached to the trough, and completely covers the float.

In this connection it should be mentioned that the shock of the two occulting-bars of the photochronograph, attached to the freely floating telescope, has no influence whatever on the character of the trails. Evidence, even, of short periodic disturbances, is lacking. For the slight vertical displacement of the dots occasionally detected are no greater than the lateral ones simultaneously observed, and these latter are attributed to the unsteadiness of the atmosphere. These disturbances, due to lateral refraction, are a constant phenomenon of photographic transit work (see pp. 13 and 32), and are perfectly familiar to all observers.

2. The *method* of determining latitudes, for which this instrument has been designed, is evidently that of equal meridian zenith-distances of north and south stars, variously named after *Roemer*, *Horrebow* and *Talcott*, and now generally used for determining polar variation. For this purpose, pairs of stars have been selected within 30° zenith distance, differing less than 15 minutes of arc in zenith distance, but at least 5 minutes apart in their meridian passage. There must be at least 8 minutes between any two successive pairs.

The plate as seen under the microscope presents two star trails, broken up by the photochronograph into a series of dots and blank spaces marking the seconds, with two or three larger dots marking the half-minutes. There is nothing else to be seen; no reticle line or wires for reference, so essential in photographic transits, (see page 12.) Yet the two trails thus constituted, contain all the elements for the measurements required, viz. : the direction of the parallel, given by the diurnal motion, the time of the meridian passage by the photochronograph, and the value of one revolution of the micrometer-screw, by the dots made by the same. These three elements are, of course, given for every pair of stars. Besides, the plate faithfully records any disturbance whatever of the instrument.

3. The value of one revolution of the micrometer screw in the *microscope* could be determined from each individual trail, as described on page 28. It proved so constant, however, that in the final reductions the mean value from a number of plates was applied. For this purpose it would suffice theoretically to measure the distance between two of the extreme dots and divide by the number of seconds falling between them. But the lateral refraction, mentioned on page 32, made it advisable to take the mean of five consecutive dots at either end of the trail. The wire of the micrometer was first made to coincide with the trail of the southern star on each plate, and then turned 90 degrees by means of the position circle, making it perpendicular to

the trail before determining the screw value. Twelve trails measured in this way gave the following result:

TABLE I.

Plate.	1 Revolution.	v
1	32".186	0".03
1	281	6
13	166	5
14	236	2
14	176	4
15	150	7
16	189	3
17	145	7
22	212	0
29	244	3
44	269	5
60	244	3
Mean.	32".216	$\pm 0".009$

The *errors of the screw*, progressive and periodic, have been fully determined (see p. 20), and are applied to all the measures.

4. The first attempt at the photographic *determination of latitude* was made May 3d, 1892. The strong moonlight did not appear to interfere with the work, especially as the eye-end of the telescope was protected by a cloth bag, and the roof-shutters were opened only when the star was near the meridian.

The first thing to look for under the microscope is the *dot* which marks the *meridian passage* of the star. As the trail is only about a minute of time in length, the whole of it is seen in the field at once. The position, east or west, of the telescope, noted in the observing book, gives the direction in which the dots, marking the seconds, are to be counted from

the pauses indicating the minute or half-minute. The following simple rule serves as a guide. The plate is inserted in the microscope holder in such fashion that its number is upwards and the film faces the observer. If the trail is photographed with the telescope on the *West* side of the pier, the star enters the field of the microscope apparently from the *right*; if *East*, from the *left*. The known R. A. of the star for the day of observation, with the clock correction, show at once the point in the trail where the star crossed the meridian: at this point the trail is bisected lengthwise.

5. The bisection can be made all the more accurately, owing to the fact, that an *equal number of dots on either side of the meridian point can be bisected simultaneously*, and the bisection can be *repeated ad libitum*.

This alone would appear to vindicate for the photographic method a great superiority over the visual, where the bisections must frequently be made in inconvenient positions, and at inconvenient temperatures, where the object to be bisected is in motion, and where no account can be taken of the unsteadiness of the atmosphere, except by making two or four additional bisections, symmetrically distributed. If the bisection is unsatisfactory, or missed altogether, the star is lost for the night and the observation is worthless. Whereas the photographic trail, even if it be a poor one, is always valuable as a permanent record of the state of the atmosphere, shows the defects of the observation, and, in so doing, is frequently suggestive of the proper precautions for the future. A further advantage of the method is, that it isolates the *error of bisection* from all the others, which is almost impracticable in the visual method.

Before going into the results of this investigation, it must be confessed that the *microscope*, which is the one described on page 15, is hardly suitable for measuring latitude trails. The eye-piece has no motion, and hence the bisections of the trails are affected by distortions of the field. This inconvenience entailed another, and a very grave one, viz., that only the lowest power eye-piece, magnifying some 30 diameters, could be used; whereas the trails can profitably stand a much higher power.

These disadvantages, be it said by way of parenthesis, do not affect the measurements of the photographic transits. There a low power is preferable, on account of the low intensity of many of the dots, and where the dots, equally distant from the centre of the field, are always combined into pairs (see page 24). It is only with these considerations before the mind that a fair judgment can be passed on the following results.

Each bisection has been made 10 times. From the mean of these 10 readings the residuals v of the single readings were formed, and the sum of their squares [v^2] computed.

This sum varies from 0.0024 to 0.0004 revolutions of the micrometer screw. The *average* sum for 10 star trails was found to be

$$[v^2]=0^{\text{R}}001178.$$

This corresponds to the probable error of the mean of ten readings of a single trail :

$$r=\pm 0^{\text{R}}0024=\pm 0''.08$$

and consequently to the probable error of the measured difference of zenith distance :

$$r=\pm 0''.11.$$

From this result it may be safely inferred that the probable error of the distance between a pair of stars in the visual method of latitude determinations, is more than one-tenth of a second. In the photographic method, by means of a suitably constructed microscope of high magnifying power, it may be reduced to less than this amount.

6. Finally, a few *preliminary results* are here given as regards the latitude of Georgetown College Observatory.

The reductions were made by means of the formula :

$$\phi=\frac{1}{2}(\delta+\delta')+\frac{1}{2}(m-m')+\frac{1}{2}(r'-r),$$

where ϕ is the latitude of the Observatory, δ the declination of the star, and r the refraction.

This formula differs from the one employed in connection with the ordinary zenith telescope, by the omission of the term :

$$\frac{1}{2}(i+i'),$$

which regards the readings of the spirit-level.

The reason for this omission is that the instrument when reversed keeps its own level. This fact implies a two-fold advantage that deserves some attention.

Although many astronomers may perhaps consider M. D'Abbadie's words somewhat exaggerated when he says that "the spirit-level must for the future be excluded from all astronomical observations where the last degree of exactness is desired" (Bulletin Astronomique, T. IX, Mars 1892, p. 93), yet they will unhesitatingly allow that the spirit-level is the weak point in the zenith telescope.

As long as the spirit-level forms an essential part of this instrument it will be hardly profitable to insert a sensitive plate at the eye-end and find the term $\frac{1}{2}(m-m')$ by photography, whilst the other term $\frac{1}{2}(i+i')$ remains subject to all the inconveniences and errors of the visual method.

In the case of the Floating Zenith Telescope, however, the whole burden of nightly measuring is taken away from the observer and thrown solely on the sensitive plate. This constitutes the second advantage just mentioned.

There is still another simplification of the usual formula which deserves mention. Practically, the bisection of a star image is always made a little out of the meridian, and a "reduction to the meridian" proportional to the hour angle is given in the text-books. No such reduction applies to the photographic method, since by means of the photochronographic record, the hour angle of the dot to be bisected is invariably reduced to zero.

In the following Table II, the star numbers are those of the Pulkova Meridian Circle Catalogue (Vol. VIII), except the five smallest numbers, which are from the Berlin *Jahrbuch*.

The declinations have been taken from the Catalogue without applying any systematic correction. In the last column, however, the latitude is given as it would result from Safford's Catalogue.*

The simple mean of the separate results has been taken without regard to the errors of the given declinations.

TABLE II.

1892, May.	Stars.	δ	δ'	$\frac{1}{2}(\delta + \delta')$	Microm.	Refr.	ϕ	S
9	159, 1747	33° 41' 6".0	44° 4' 38".5	38° 52' 52".25	+1' 34".01	+0".03	38° 54' 26".29	
3	1778, 1796	64 56 51.8	12 52 38.9	38 54 45.35	—0 19.56	—0.01	25.78	
8		52.7	39.3	46.00	20.84		25.15	
8	444, 446	59 0 7.1	18 58 15.0	38 59 11.05	—4 45.02	—0.09	25.94	
9		7.3	15.1	11.20	—4 45.11		26.00	
8	447, 1929	63 18 28.5	14 42 39.2	38 60 33.85	—6 7.91	—0.12	25.82	26".12
3	1998, 2039	24 24 57.3	53 27 58.1	38 56 27.70	—2 1.96	—0.04	25.70	27.50
7		58.0	59.1	28.55	—2 3.32		25.19	26.99
8		58.1	59.4	28.75	—2 3.05		25.66	27.46
9		58.3	59.7	29.00	—2 3.65		25.31	27.11
8	2103, 2112	42 1 33.3	33 0 23.0	38 60 58.15	—6 29.88	—0.11	28.16	25.51
3	2135, 195	63 39 42.9	14 11 20.5	38 55 31.70	—1 5.26	—0.02	26.42	26.22
8		44.4	21.0	32.70	—1 6.08		26.60	26.40
3	2157, 2180	38 15 13.8	39 41 28.8	38 58 21.30	—3 55.08	—0.07	26.15	26.70
3	2343, 2355	39 57 47.5	37 38 10.4	38 47 58.95	+6 27.13	+0.11	26.19	25.99

$$\phi = 38^{\circ} 54' 26''.02.$$

*Mean Declinations of 2018 Stars, &c., prepared under the direction of Lieut. George M. Wheeler, Corps of Engineers, U. S. Army, Washington, 1879.

It is desirable to state here that the above results are not considered final, because the declinations will have to be carefully scrutinized when the material is more abundant, and because of the defective construction of the microscope previously mentioned.

Two conclusions, however, may be drawn from these results. *First*, that the photographic method is as applicable to *latitude* determinations as it is to those of *longitude*, which have been fully described in the preceding publication. In both cases fewer stars, indeed, can be observed in a given time than by the usual method, but this disadvantage seems amply compensated by the accuracy of the single results.

Secondly, that the latitude determinations for this Observatory present *no evidence of secular variation* within the last 46 years. The late Father Curley, in his publication of 1852, page 215, gives as the result of 7 observations of Polaris, and as many of α Ursae Majoris, at upper and lower culminations, the latitude (1846, Sept. 16—Nov. 30):

$$\phi = 38^{\circ} 54' 26''.07,$$

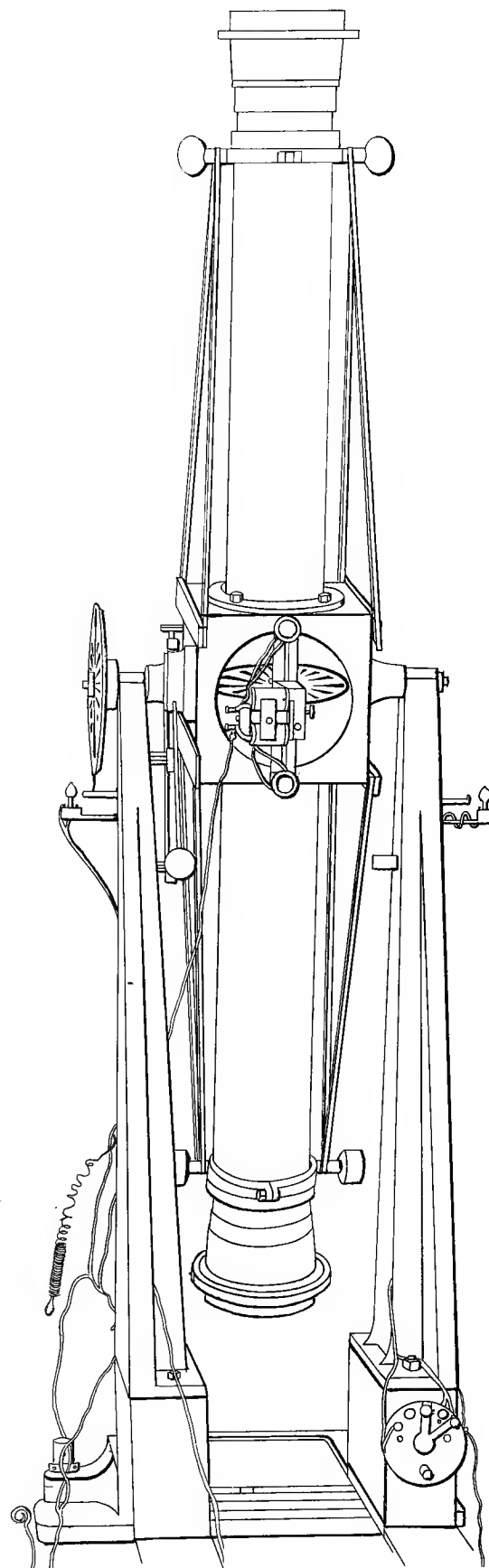
and as the result of 180 other Almanac stars: $38^{\circ} 54' 25''.6$, for which the time of observation is not given.

The intention is to make this Observatory a *permanent station for studying the periodic variations of the Pole*. A second permanent latitude station is, at our instance, being erected at Manila, in the Philippine Islands. It will be furnished with a floating zenith telescope and latitude photochronograph like those here described. The future director of that station, Fr. Joseph Algué, S. J., is now at this Observatory, with the view of familiarizing himself with this method. Since Manila is almost opposite Washington in longitude, these two stations seem to be well adapted for controlling the periodic variations of the Pole by a uniform method, in a direction almost perpendicular to the meridians of Berlin and Honolulu, where simultaneous observations are carried on at present.

GEORGETOWN COLLEGE OBSERVATORY.

THE REFLECTING ZENITH TELESCOPE.

STORMONT & JACKSON,
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WASHINGTON, D. C.
1893.



THE REFLECTING ZENITH TELESCOPE.

PREFACE.

In the preface of the preceding treatise two ways of taking latitudes by photography and without zenith levels were pointed out, based respectively upon the *reflecting* and the *floating* principles.

The latter is fully described in the treatise just mentioned, and the former has now been successfully tried by Father José Algué, S. J., a student of this Observatory. The device of the reflecting zenith telescope, which will be described in the following pages, is entirely due to him, whilst the mathematical theory has been worked out by Father John T. Hedrick, S. J.

We may be allowed, in this place, to mention some further experiments that have been made here in the same line.

The two methods described in this and the preceding treatise are not the only ones available for photographic determinations of latitude. In the foregoing preface (page 39) two references were given to the *Astronomische Nachrichten* (No 2982, p. 81, and No. 3015, p. 241), of which the latter deserves especial notice. There Professor Küstner suggests that the micrometer of a common zenith telescope might be replaced by a photographic camera, whilst the spirit-levels would be read in the usual way. No intimation was given, however, as to the method of determining the value of a revolution of the microscope micrometer.

In order to test various photographic methods of determining the latitude and thus to be enabled to decide upon the most convenient one for permanent use, this plan has also been tried at our Observatory. The instrument employed was an ordinary zenith telescope, belonging to Mr. G. N. Saegmuller, which is now on exhibition at the World's Fair in Chicago.

It has a 3-inch visual object-glass and two latitude levels. The micrometer was removed and replaced by a plate-holder.

The screw-value of the microscope micrometer was determined in the same way as in the other two methods, by means of a *photochronograph*.

There are thus three photographic methods of determining latitudes which have been tried here, for the first time as it would seem, and have been found practicable.

Each of them has its own advantages in certain directions, which, however, must be purchased by disadvantages in other ways.

It will be a matter of opinion with observers, to which to give preference. Yet, the fact that the last mentioned method differs least from the visual method, and that the ordinary zenith telescope now in use can readily be adapted for it, will in all likelihood recommend its general introduction.

GEORGETOWN COLLEGE OBSERVATORY, *June* 16, 1893.

J. G. HAGEN, S. J.

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THE REFLECTING ZENITH TELESCOPE.

By JOSÉ ALGUÉ, S. J.

PART I.

DESCRIPTION OF THE INSTRUMENT.

1. *Double Telescope.* The construction of the instrument may be gathered from an examination of Plate V. In appearance it is not unlike a transit instrument, but it has two object-glasses, one at each end of the same tube, forming a double telescope.

The objectives, by Brashear, are almost exactly alike. They have a clear aperture of 10.5 cm. and a focal length of about 64 cm. This particular focal length was adopted in order to secure the trails of stars of the 7th photographic magnitude, and to diminish flexure of the telescope. These two lenses have a common focal plane in the interior of the central cube, where sensitive plates are placed. For the purpose of further diminishing flexure, four metal braces extend from near the cell of either object-glass to projecting arms on the corresponding edges of the cube. Cone-shaped tubes of some alloy of aluminum would seem to be preferable. The handles near the objectives are intended to facilitate the setting and moving of the telescopes. There is no eyepiece, and the instrument is exclusively photographic.

It is intended primarily for latitude determinations by the usual method of equal meridian zenith distances, but it may also be used as a transit for time observations. In the former case both object-glasses are indispensable; one receiving the light of the star directly, the other by reflection; in the latter, either lens will serve the purpose. The instrument is provided with a striding level and a reversing apparatus. For latitude determinations alone the latter is not needed, though it may be used. (See page 70.)

2. *Plate-holder and Reticle.* The plate-holder consists of a thin glass plate, firmly secured to a brass frame-work near the centre of the cube. One of its faces is in the common focal plane of the two objectives. The sensitive plate is placed with its film in contact with

this face. It slips easily into position and is held firmly by two flat springs. The light from one lens reaches the sensitive film by passing through the glass plate-holder, while that from the other lens falls on the opposite face of the film after passing through the glass of the photographic plate; thus the light from either lens has to pass through a layer of glass before reaching the film.

The glass plate-holder does not necessarily require any reference lines; but for the sake of convenience, two lines at right angles are engraved on the focal face. These lines are photographed on each plate, in the manner described on p. 11. The horizontal line may be conveniently termed the *latitude wire*, and the vertical one the *transit wire*. The latter will be of service when the instrument is used for time determinations, although it also marks the meridian passage in the latitude trails. The use of the other line will appear in Part III, No. 2.

3. The Stand and Base. The rotation axis rests on an iron stand 93 cm. high with a metal base 51 x 69 cm., provided with screws for leveling and for adjustment in azimuth, and this base in turn is placed on two plates of iron. The instrument was temporarily installed in the meridian circle room of the Observatory. The base rested on two ledges on the inner faces of the stone piers, and was some 160 cm. above the floor.

4. Reflecting Apparatus. The reflecting apparatus consists of a trough or mercury basin, 18x200 cm. It was placed between the piers, more than two meters distant from the rotation axis of the instrument. Both the instrument and the mercury trough rested on the piers and were consequently isolated from the floor. It is advisable to place the mercury as far below the instrument as convenient, so as to reach stars close to the zenith, and to protect the reflecting surface from disturbance.

5. The Photochronograph. The photochronograph plays the same part in this instrument that it does in the floating zenith telescope, described in the preceding pages, viz.: it gives the screw value from each plate and determines exactly on each trail the point of meridian passage of the star. Among the various shapes possible, an *occulting disk* has been selected.

It consists of two aluminum disks, 13 cm. in diameter, mounted on an axis which is perpendicular to the plate-holder and passes through the prolongation of the vertical wire. The disks are 25 mm. apart, and are opposite to the two faces of the plate-holder. The sensitive plate is slipped into position between one of them and the plate-holder, in a direction parallel to the vertical wire. Sectors are cut out of the disks, of equal width with the metal left between them. These are called here spaces and spokes. The disks are rotated by an anchor armature engaging a toothed wheel on their axis. The circuit of the electro-magnet

passes through a clock provided with a Gardner spring contact, as are the other clocks of this Observatory. The spring contact alternately makes and breaks the circuit at intervals of one second. Each make or break advances the toothed wheel half a tooth, and the spaces and spokes are thus swept across the field in front of the two faces of the sensitive film, alternately transmitting to it or cutting off from it the light from any passing star.

This particular arrangement permits an adaptation of the time of exposure and occultation to stars of different magnitudes or different rates of diurnal motion, without changing the interval between successive makes and breaks in the circuit. If the number of spaces is that of the teeth of the wheel, or the number of spaces and spokes together is twice that of the teeth, then at each make or break a space is replaced by a spoke, and *vice versa*. A complete make and break moves the wheels through a whole tooth and replaces a space by a space. Hence a star in the field of either objective is alternately allowed to act on the film and is occulted, each during one second. If the number of spaces is half that of the teeth, and the spaces and spokes are again of equal width, then the toothed wheel must be moved a whole tooth to entirely replace a space by a spoke. Hence the time of exposure or occultation will be that of a complete make and break, or two seconds. In the same way the time may be increased to three or more seconds. The instrument is furnished with different sets of occulting disks.

6. The Setting Circle. The setting of the telescope is effected by means of a graduated circle which reads to minutes of arc by means of a vernier. A ruby incandescent lamp is placed just in front of the vernier. The circle is provided with the usual clamp and slow motion. This setting of the instrument on the mean zenith distance of a pair of stars, by means of the circle, is sufficient to bring the stars within reach of the disk photochronograph, and thus it enjoys the advantage of the floating zenith telescope, where both stars are brought within the range of the double bar photochronograph by the circle only, and without the aid of the eyepiece.

7. Advantages and Disadvantages of the Instrument. From the foregoing description, the advantages and disadvantages of the present arrangement, in comparison with other forms of the zenith telescope, will appear.

The first disadvantage is, that the pairs nearest the zenith are excluded, and this in proportion as the mercury basin is brought nearer the instrument. In the instrument as constructed, with the mercury $1\frac{1}{4}$ m. from the objective, stars can be taken at 3° zenith distance with the full aperture, and nearer still if the full aperture is not necessary.

In the next place, the *reflected* trails are not as sharp and uniform as these *directly* photographed, and may be entirely obscured by surface waves on the mercury. However, this

apparent defect is really useful, since the reflected trails possess these individuating features, their intensity varying from point to point. Since from the observing-book it is known which of the pair of stars has been photographed by reflection, these slight disturbances of the mercury serve to identify the trails.

A more serious disadvantage of this method is the introduction of the instrumental error due to flexure by the action of gravity. This error enters the result, as the mean of the flexures of the two tubes, and not as their difference, as in ordinary telescopes. But the effect is opposite in sign according as the northern or southern star of a pair is observed by reflection. Hence, the observations can be paired so that it will be eliminated. This is shown in Nos. 3, 4 and 5 of the part on the theory of the instrument.

The *advantages* of the instrument are: *first*, that it is *not touched* by the observer between the meridian passages of the two stars of the pair; and, *secondly*, that these two transits may be *simultaneous*, as each has its own object-glass. Both advantages are peculiar to this double zenith telescope, and cannot be enjoyed in any instrument with a single objective. Hence, instrumental changes from temperature or other disturbing agencies, during the passage of a pair of stars, are reduced to a minimum, and in addition, more pairs can be taken in a given time than by any other method. In fact, two pairs, which cross the meridian within less than 7 minutes of time, have been taken on one plate, and it is quite probable that two pairs could be photographed within 5 minutes, if it should be necessary.

Finally, any given pair requires the employment of only about half the length on the micrometer screw, that is required in the usual method. Or, with a given length of screw, a pair can be measured whose difference of zenith distance is about twice as great as is usual. For the reflection from the mercury places one part of the sky symmetrically with regard to the collimation axis, so that only so much of the screw is needed as corresponds to half the difference of zenith distance (see Pl. VI, Fig. 1). When on one plate we take two pairs in which the micrometric corrections are of opposite signs, we shall have to measure only about the difference of the two micrometric corrections.

It will, of course, be a matter of experience to determine the relative weights of these advantages and disadvantages. The question can be decided only by a long series of systematic observations, compared with similar series obtained by other methods.

PART II.

ADJUSTMENT AND USE OF THE INSTRUMENT.

1. Focus and Level. The focus of each lens was readily determined by the method already described on page 15. The draw tubes were then firmly clamped at the places thus determined. The two focal lengths may differ considerably without any theoretical inconvenience, as the screw value is determined for each objective separately. The levelling of the rotation axis was effected by means of a striding level, and four screws at the foot of the iron stand.

2. Collimation. As this instrument differs from others, in having two object-glasses, we shall have to give some definitions regarding collimation, in order to make the following statements intelligible.

We shall first take the collimation of a single object-glass, e. gr. I, in which case the collimation will mean what it does in a transit instrument.

The transit wire was first adjusted for objective I by pointing on a terrestrial object, reversing the rotation axis and moving the plate-holder or reticle until a reversal of the axis did not displace the object from the wire. In this way, one-half of the instrument is adjusted like a transit. Since the instrument has no eye-piece, the image of the terrestrial object may be received on a piece of ground glass fastened to the plate-holder, the ground surface taking the place of the sensitive film.

We will now call the *line joining the optical centres of the two object-glasses*, their common collimation axis, or simply the *collimation axis* of the instrument. This axis will pass through the reticle plate at a point P_o , which will in general not coincide with the point of intersection of the transit and latitude wires. We will call its distances from these wires its *horizontal and vertical collimations* respectively.

The horizontal collimation of the point P_o , ought to be very small in order that the points of the meridian passages of the two stars of a pair may be practically coincident with the transit-wire. Its reduction to zero cannot be made by moving the transit-wire, since this has already been adjusted with regard to the rotation axis for lens I. It must, therefore, be effected by moving object-glass II parallel to the plane of the reticle-plate, in the direction east and west. The cell of this objective has been provided with adjusting-screws for the purpose.

The method consisted in pointing object-glass I on a distant terrestrial object, and moving the whole instrument in azimuth, until the image fell on the transit-wire; then pointing object-glass II on the same object without changing the azimuth, and adjusting the cell until

the image again fell on the transit-wire. In this way the collimation axis of the instrument is made to pass through the transit-wire, perpendicularly to the rotation axis.

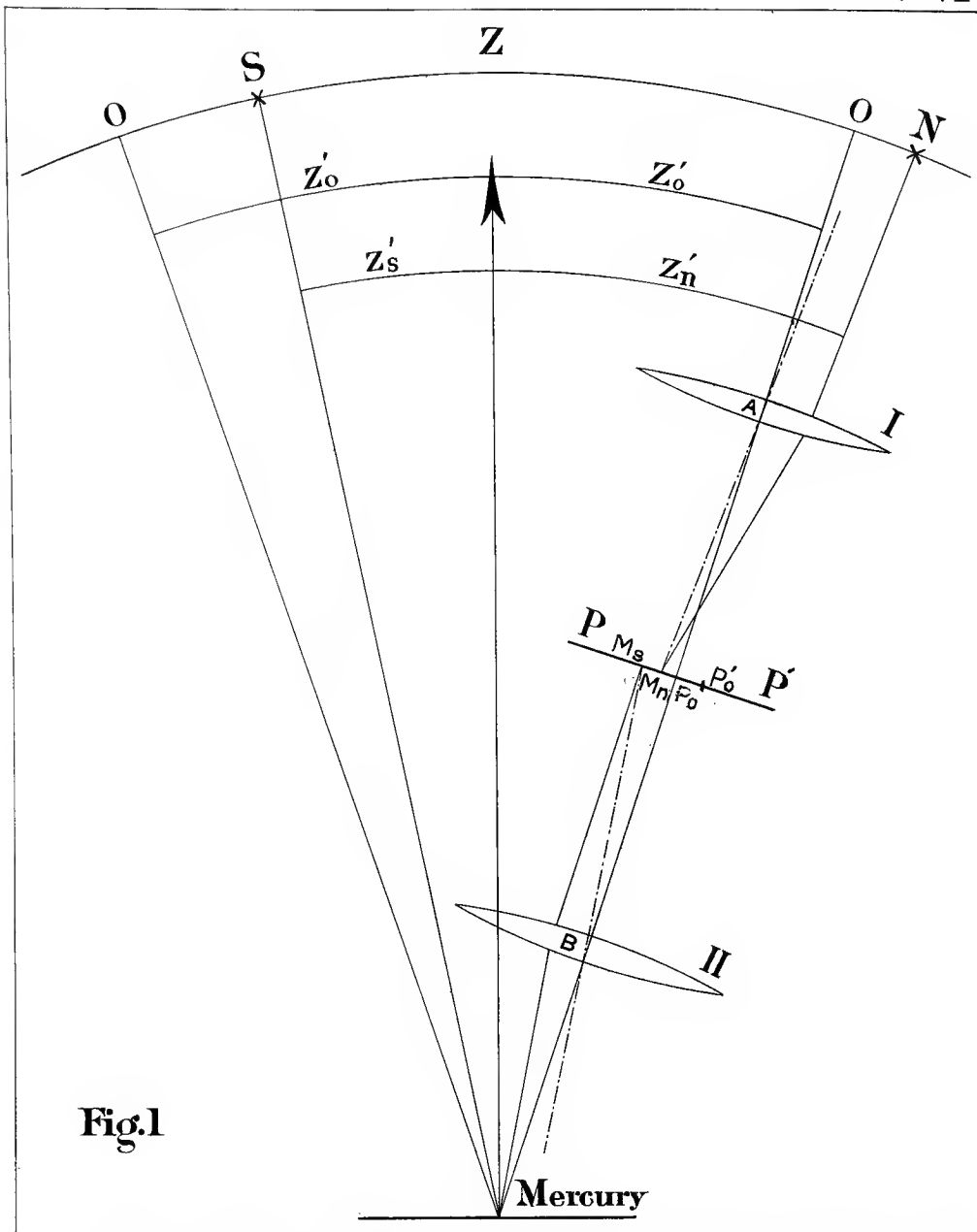
The vertical collimation of the point P_o is adjusted by bringing the point P_o near the latitude wire. It has been found convenient, however, not to make this collimation correction a small quantity, but to keep it larger than one minute of arc. Theory, in fact, shows no reason why this correction should be small; and, on the other hand, if the correction is large, no doubt can occur as to whether it be positive or negative. The adjustment can be made by moving either the reticle-plate or the cell of object-glass II. In the present instance the latter has been done, as the cell had adjusting-screws in this direction also. The operation consists in first pointing object-glass I on some object, so that its image falls on the latitude wire, and reading the setting circle; then turning the instrument in the meridian 180° , and clamping. If the image then appears displaced, it must be brought back to position, by moving either the reticle-wire, or, as was actually the case, the cell of II.

The objects chosen were, first, a terrestrial one, and then the sun, which at the time was near the equator. Its bright image, which remained four minutes on the reticle, was well adapted for the purpose. By repeating these processes the *three collimations* can be reduced to any desired quantity.

3. The *azimuth* of the instrument, and the *zero point* of the circle, were also adjusted by the image of the sun; the time of transit and the declination being taken from the Almanac.

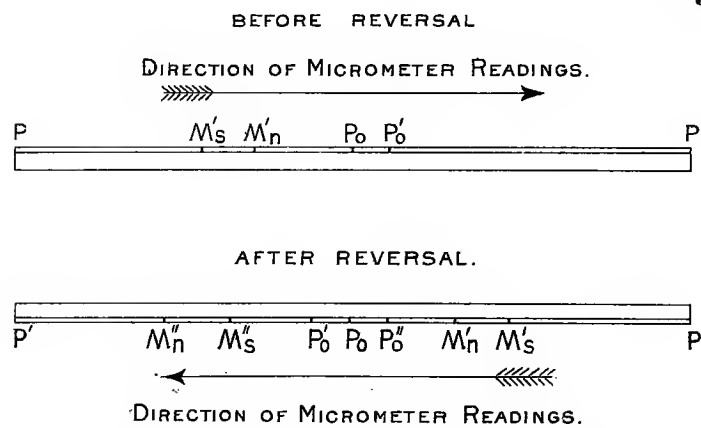
4. *Photographic plates.* The sensitive plates are similar in every respect to those used in transit observations and latitude work with the floating zenith telescope (p. 49). They can be inserted from one side only. The space covered by the photochronograph does not exceed $1\frac{1}{2}$ inches square.

5. *Method of taking the Photographs.* The plate is first inserted, then by means of the circle, which reads from two opposite zeros up to 90° each way, the instrument is set to about the mean zenith distance of the pair of stars to be observed. The instrument is then clamped, and left untouched, until both stars of the pair have trailed across a sufficient extent of the plate. If a second pair is to be taken on the same plate, the instrument is unclamped, reversed and again set and clamped. Finally, a light is held before the objective that is nearer the reticle plate, to photograph on the plate the two wires and also two arrows, marked E and W, which show the direction of the diurnal motion for the two different positions of the setting circle. If necessary, the armature of the photochronograph may be worked by hand, so as to uncover the vertical wire.



MERIDIAN SECTION OF THE PHOTOGRAPHIC PLATE.

Fig. 2



In Plate VI., Fig. 1. NZS = the meridian, Z = the zenith.

N = the northern star, S = the southern star.

$P P'$ = the meridian section of the sensitive film.

I and II = the two objectives.

P_o = the point of intersection of the collimation axis with the film.

M_s = the meridian point of the trail of the southern star.

M_n = the meridian point of the trail of the northern star.

It is easily seen from the figure that the trails of the two stars of a pair fall on the same side of the collimation axis, and that their difference of zenith distance is equal to the sum of the distances of their trails from the axis. If the setting were exactly the mean zenith distance, the two trails would cover each other, but by intentionally changing the setting, the two trails can be made to separate by any convenient amount. In one case, where the two trails were nearly coincident, measures were still feasible, because the interruptions made by the photochronograph did not coincide.

6. Work of the Photochronograph. The telescope once set, a switch in the clock and photochronograph circuit connects electrically the clock and photochronograph. The latter, as the spaces and spokes replace each other, allows all the stars, within the field of either lens, to imprint their trails on various parts of the plate, and, at the same time, breaks these trails every second or every two or more seconds. In practice a two second exposure has proved convenient for both north and south stars.

PART III.

THEORY AND FORMULÆ.

1. *The Latitude from Two Pairs.* Let δ'_s be the true declination of the southern star; z'_s , its apparent zenith distance; and r'_s , the correction for refraction, and δ'_n , z'_n , and r'_n , the corresponding quantities for the northern star. Then

$$\phi = \delta'_s + (z'_s + r'_s) \quad \phi = \delta'_n - (z'_n + r'_n) \quad (1)$$

Also, let m'_s , m'_n and m_o be the readings of the micrometer microscope on the points M_s , M_n and P_o , of Fig. 1, respectively, let R_1 and R_2 be the values in arc of one revolution of the micrometer for the objectives I and II, respectively, and let z'_o be the equal zenith distance of the two prolongations of the optical axis. To fix the ideas, the micrometer readings are supposed to increase from P towards P' .

We have from the figure by inspection :

$$\left. \begin{aligned} z'_s - z'_o &= M_s B P_o = (m'_s - m_o) \cdot R_2 \\ z'_n - z'_o &= M_n A P_o = -(m'_n - m_o) \cdot R_1 \end{aligned} \right\} \quad (2)$$

Substituting the values of z'_s and z'_n from these equations in equations (1) and adding, we have

$$2\phi = (\delta'_s + \delta'_n) + (r'_s - r'_n) + (m'_s - m_o) \cdot R_2 + (m'_n - m_o) \cdot R_1. \quad (3)$$

The instrument is now reversed, so that the two ends P and P' of the sensitive film are interchanged, either by reversing the horizontal axis of the instrument, or, preferably, by turning the instrument end for end about this axis, and another pair of stars of any mean zenith distance is taken on the same plate. Distinguishing the quantities for this second pair by double accents, we have

$$\left. \begin{aligned} z''_s - z''_o &= -(m''_s - m_o) \cdot R_1 \\ z''_n - z''_o &= (m''_n - m_o) \cdot R_2 \end{aligned} \right\} \quad (2')$$

$$2\phi = (\delta''_s + \delta''_n) + (r''_s - r''_n) - (m''_s - m_o) \cdot R_1 - (m''_n - m_o) \cdot R_2 \quad (3')$$

Since the direction of the plate with regard to the zenith has been reversed, while in the microscope both pairs of trails are measured in the same direction, the signs of the second members of equations (2') are opposite to those in equations (2). See also Fig. 2.

Since the plate has not been disturbed, the point P_0 and the micrometer reading m_0 will be the same, flexure aside, for both pairs. Hence, adding equations (3) and (3'), dividing by 4, and putting $\Sigma\delta = \delta'_s + \delta'_n + \delta''_s + \delta''_n$, $\Sigma\Delta r = (r'_s - r'_n) + (r''_s - r''_n)$, we have

$$\phi = \frac{1}{4} \Sigma\delta + \frac{1}{4} \Sigma\Delta r + \frac{1}{4} [(m'_n - m''_n) \cdot R_1 + (m'_s - m''_s) \cdot R_2] \quad (4)$$

The direction in which the differences within the parentheses are to be taken depends upon the direction in which the micrometer readings are supposed to increase, and would be the other way, if the readings increased towards the end of the plate nearer the zenith in the first observation. But it is evident from the figure, that it is independent of the part of the plate on which the trails are formed, whether this be the same or different for the two pairs.

2. The Latitude from a Single Pair. Equation (4) requires the observation of two pairs of stars for a single value of the latitude. There is but little, if any, inconvenience in this, as two pairs sufficiently near in time can usually be found, and the resulting value of the latitude has all the accuracy of the mean of two separate pairs in the ordinary method. But by photographing the horizontal wire on the plate, and determining its collimation error or distance from what we have called the collimation axis of the instrument, a value of the latitude can be found from a single pair.

Let m_w be the micrometer reading on the wire image, and let $c = m_w - m_0$ or $m_0 = m_w - c$. Then equation (3) will become

$$2\phi = (\delta'_s + \delta'_n) + (r'_s - r'_n) + (m'_s - m_w) \cdot R_2 + (m'_n - m_w) \cdot R_1 + c(R_1 + R_2), \quad (5)$$

which gives a value of ϕ when c is known.

If we substitute the value of m_0 in equation (3') we have

$$2\phi = (\delta''_s + \delta''_n) + (r''_s - r''_n) - (m''_s - m_w) \cdot R_1 - (m''_n - m_w) \cdot R_2 - c(R_1 + R_2). \quad (5')$$

Or, distinguishing by accents the two values of ϕ found from (5) and (5') by neglecting the last term, we find the correction for the collimation error of the wire to be applied to a latitude from a single pair.

$$\text{Wire correction} = \frac{1}{2} c (R_1 + R_2) = \frac{1}{2} (\phi'' - \phi') \quad (6)$$

The sign given by (6) is that of the correction to be applied to the latitude from an observation in which the P end of the film was nearer the zenith, and ϕ' is the latitude from that one of a double pair, for which the instrument had this position.

The value found from (6) is affected, of course, by the flexure, if the two pairs have not the same zenith distance, and by the errors of the declinations used for the stars of the pairs. But, supposing the flexure correction known, the error from the second cause may be made insensible by taking each evening a sufficient number of double pairs. The value of c will still

be affected by a small error, namely, the mean of the errors of the declinations used each night, but this will not affect the relative divergences of the latitudes given by the separate double pairs of the night, from which are deduced the corrections to be applied to the declinations. These, consequently, can be computed after observations of a year or more by Dr. Albrecht's method of a closing chain of groups of pairs. When this has been done it will be an easy matter to go over the first results and correct them for the error in the assumption of correctness in the declinations used in the first computation. It is evident that the value of c should be determined from those pairs only, which form part of the chain of groups.

3. The Effect of Flexure. In deriving the formulæ (4) and (5), we have supposed that there was no sensible flexure of the telescope tube by gravity. We have now to see what modifications have to be made to take it into account.

Let F_1 and F_2 be the linear displacements of the optical centres of the objectives I and II, respectively, when the telescope is horizontal. For present purposes it will be sufficient to suppose that the flexure is proportional to the sine of the zenith distance. Hence, when the telescope is directed to a point of the sky whose zenith distance is z'_o , the linear displacements will be $F_1 \sin z'_o$ and $F_2 \sin z'_o$. The focal lengths of the two objectives being nearly equal, the displacement of the collimation axis where it pierces the sensitive film, or of the zero point of the measurements, will be $\frac{1}{2}(F_1 + F_2) \sin z'_o$. Or, if we put f for the micrometer equivalent of $\frac{1}{2}(F_1 + F_2)$, the displacement will be, in micrometer revolutions, $f \sin z'_o$.

In the position of the instrument represented in Fig. 1, Pl. VI, the displacement will be towards P' . The displaced zero point is indicated by P'_o . This point, P'_o , is that to which the measures should be referred. Indeed, if it were measurable in the microscope, there would be no correction to the observation on account of flexure, as the zero point and the star trails would be displaced by the same amount. Since the displacement is in the direction of increasing readings, we must substitute for m_o in equations (2), $m_o + f \sin z'_o$, or we must add to the second members of (2) the terms $-f R_2 \sin z'_o$ and $+f R_1 \sin z'_o$, and to the second member of equation (3), the term $-f(R_1 + R_2) \sin z'_o$.

When the instrument is reversed for the second pair, the displacement of the zero point will be in the same direction in the instrument but in the opposite direction on the film, or in the direction of decreasing micrometer readings. (See also Pl. VI., Fig. 2, where P''_o is the displaced zero point after reversal.) Hence, in equations (2'), for m_o we must substitute $m_o - f \sin z''_o$. The second members of (2') need the corrections $-f R_1 \sin z''_o$ and $+f R_2 \sin z''_o$, and the second member of equation (3'), the correction $-f(R_1 + R_2) \sin z''_o$.

Hence, the second member of equation (4) will need the correction $-\frac{1}{4}f(R_1 + R_2)(\sin z'_o + \sin z''_o)$, or the latitude found by it is affected by the means of the flexure errors of the two pairs of stars.

If the micrometer readings be supposed to increase from P' towards P , the signs must be changed within the parentheses of the second members of equations (2) and (2'); but at the same time the sign of the flexure term to be added to m_o will change so that the flexure corrections is independent of the direction of measurement in the microscope.

4. The Determination of the Flexure. The effect of the flexure is an apparent shift of the zenith towards the part of the sky in which the stars are observed directly. Hence, if the same pairs be again observed, and those stars taken directly which before were taken by reflection, the latitude deduced will be affected by flexure to the same amount but in the opposite sense, and this, no matter what function the flexure may be of the zenith distance. The same result may be easily obtained by supposing N and S to be interchanged in Plate VI., Fig. 1. The subscript letters n and s must then be interchanged in equations (2) and (2'). The terms to be added to the second members of these on account of flexure will be the same as are given in No. 3. But since z'_s and z'_n have opposite signs in equations (1), the terms to be added to the second members of equations (3) and (3') will be respectively $+f(R_1 + R_2)\sin z'_n$ and $+f(R_1 + R_2)\sin z''_o$. The term to be added to the second member of equation (4) will be $+\frac{1}{4}f(R_1 + R_2)(\sin z'_o + \sin z''_o)$.

The observation of a double pair in this way on different nights will give us the flexure correction needed at its zenith distances. By a series of suitable combinations of pairs at different zenith distances we can determine the value of the flexure coefficient (or coefficients) and also what function the flexure is of the zenith distance. This determination is independent of the absolute declinations of the stars employed, and requires a knowledge of their variations only.

5. The Elimination of the Flexure. The observations should accordingly be so arranged that the northern and southern stars of a double pair are taken alternately by reflection. The mean of two such observations will give a value of the latitude which is free from the effect of flexure. This value requires the observation of two pairs of stars on two nights, but it has all the accuracy of the mean of the same observations made in the ordinary way, provided that the photographed star trails can be measured with the accuracy of the ordinary visual observations. That this will be the case there does not seem to be any reason to doubt. Since,

however, corresponding observations of a double pair will sometimes fail, the formula for the flexure correction should be made out in order to utilize all the observations secured.

The assumption has here been made that the flexure of the tube is the same whether one or the other face of the cube is uppermost.

6. *Photographing through the Glass Plates.* On both sides the light from the objectives has to pass through a glass plate before falling on the sensitive film. All the rays except those which fall perpendicularly, will suffer deviation. But as the angles of incidence are so small that they are proportional to their sines and tangents, the difference between the angles of incidence and refraction will be proportional to the former, or proportional to the distance from the foot of the normal from each optical centre. If the two faces of each plate are parallel, this will produce a uniform distortion of the field, and the value of one revolution of the micrometer determined by the photochronograph will be the proper one to use in measuring the latitude-trails. Any want of parallelism and other irregularities in the glass which carries the sensitive film, will produce only accidental errors. For the reticle-plate, want of parallelism in the faces would produce constant errors, and hence, care must be taken that its faces are accurately parallel throughout the portion made use of.

7. *Correction for Difference of Latitude of the Mercury.* The latitude deduced from each pair will need theoretically a small correction for the difference of latitude between the horizontal axis of the instrument and the point of the mercury at which the reflection of the collimation axis takes place, since the latter point is that whose latitude is given by the observation. The correction will be the difference of latitude itself, and will be positive when the southern star is taken by reflection, and negative when the northern star is so taken. Hence, when the observations are paired to eliminate flexure, this correction is also eliminated. The value of the correction is evidently

$$\triangle \varphi = 0.''0324 \, d \tan z.$$

where d is the distance in metres of the mercury below the horizontal axis, and z is the zenith distance.

PART IV.

PRELIMINARY RESULTS.

1. The selection of pairs for these first observations was not made systematically. Hence, the results given below are to be looked upon as merely experimental. Pairs 1 and 2, for instance, were chosen as a test for stability, and the plate was exposed for 34 minutes. This long interval did not sensibly affect the average result from four successive nights' observations, as may be seen below. Of course, in regular work, so long an exposure would rarely, if ever, occur. Again, the differential zenith distance was sometimes unduly large, as in the case of pairs 2, 4 and 9. The results, however, seem satisfactory.

2. *The Microscope Micrometer.* This is, substantially, the apparatus described on page 14, with some improvements however. To one of the arms of a heavy cast iron Y-shaped stand, is fixed a movable stage for the negatives. It is provided with rack-work for centering, by means of two rods reaching to the eye-end. The other arm is fitted with a tube carrying on one end an objective of about 20 cm. focal length, and, on the other is screwed the Saegmuller micrometer of the 19-inch equatorial now in process of construction for the Observatory at Manila.

It has two parallel *movable* wires, one of them being double, a fixed wire parallel to these, and one, perpendicular to them. The screw value was temporarily determined for each lens by the method described on page 51, which gave slightly different values for the two: the value of one revolution for lens I, being 51."614, and that for lens II, 51."744. No corrections for *errors of the screw*, either progressive or periodic, have as yet been determined for the micrometer-screw used in these measures.

3. *Aspect of the Plates under the Microscope.* The first thing to look for on the plate under the microscope is the transit-wire of the reticle, which shows approximately the point of meridian passage. The arrows automatically imprinted on the plate give the direction of the diurnal motion, and in connection with the record of the way each objective was used, indicate which end of the plate was nearer the zenith for each pair. The photochronographic breaks give besides, the exact position of the meridian point in each trail, permitting the observer to readjust afterwards the transit-wire of the instrument, if necessary.

4. *The Measurement.* The measurements were made in this way. The fixed cross-wire of the micrometer reticle was set on the transit line of the plate. The tangents to the star trails were then parallel to the movable micrometer wire. Settings were then made on the

four star trails in the direction required by formula (4). A setting was also made on the image of the horizontal wire, in order to deduce the vertical collimation. Even for a full plate the use of the vertical collimation to deduce a value of the latitude from each pair separately, although not necessary, is still of practical convenience as affording a check on errors in the measurements. A practical rule for the signs of the micrometric correction to the half sum of the declinations in a single pair is easily deduced from Fig. 1 of Plate VI. In the circumstances of the figure, *i. e.*, when the southern stars are taken by reflection, the correction is negative when the two trails fall on the upper or zenith end of the plate, and positive when they fall on the lower end of the plate. The opposite signs are to be used when the northern stars are taken by reflection. For a full plate, when no use is made of the vertical collimation the simplest thing is to follow formula (4).

The correction for refraction has always the same sign as the micrometric correction, as in any zenith telescope.

5. Table of Results. The first column gives the date of observation, the second, the number of the pair. The numbers in the third column are those of the stars in the Berlin "Jahrbuch," or in the catalogue of latitude stars in the volume for 1876, of the United States Coast and Geodetic Survey. The smaller numbers refer to the former, those greater than 900 to the Coast Survey Catalogue. The declinations used were taken from these two sources. The fourth column shows whether objective I was used for the star observed directly or for that by reflection. In every case the northern star was taken by reflection. The instrument was in the position "Circle E." for all the observations. The seventh column gives the mean zenith distance of each pair. No correction has been applied for difference of latitude of the mercury. The other columns need no explanation.

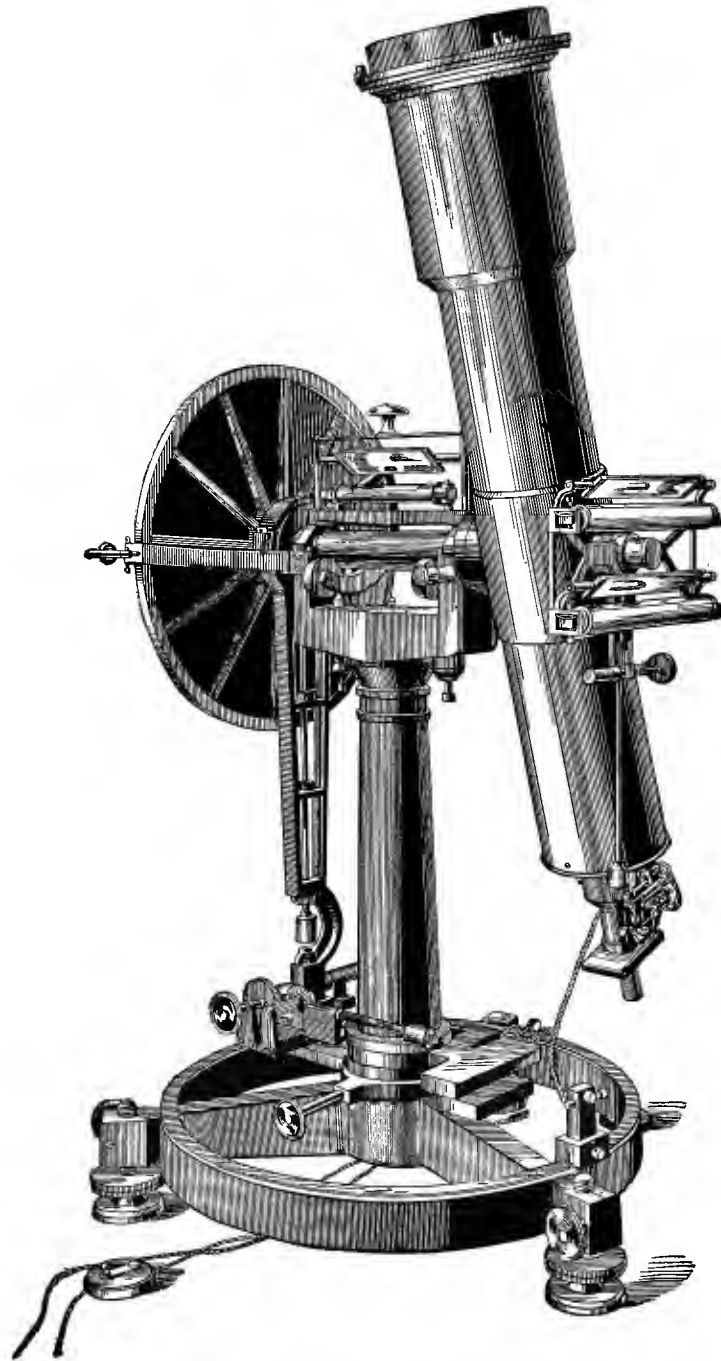
It will be seen that there is no column for the *flexure* of the tubes. The time possible for this first experimental series at this Observatory was too short to do more than find in general the working capacity of this new device. A more detailed investigation will be undertaken at the Observatory in Manila, and if the instrument proves equal to others of the kind, it will be employed for continuous observations of the variation of latitude.

GEORGETOWN COLLEGE OBSERVATORY.

THE PHOTOGRAPHIC ZENITH TELESCOPE.

STORMONT & JACKSON,
PRINTERS,
WASHINGTON, D. C.
1894.

Plate VII.



THE PHOTOGRAPHIC ZENITH TELESCOPE.

PREFACE.

The present treatise gives an account of further experiments made at this Observatory in the line of determining latitudes by photography. They are a continuation of our first trials with an ordinary zenith telescope, mentioned on page 59, with the difference, however, that the instrument is now more perfect.

Our series of experiments with the three kinds of latitude instruments described in this volume, viz., the floating, the reflecting and the ordinary zenith telescopes, is thus brought to an end. It seems to show that all the three photographic methods are capable of affording satisfactory results.

As regards the relative merits of these methods, we refer the reader to our remarks on page 60.

For the present, the instrument to be employed at this station for determining the variation of latitude, will be the one described in the following pages.

GEORGETOWN COLLEGE OBSERVATORY, *December 27*, 1893.

J. G. HAGEN, S. J.

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THE PHOTOGRAPHIC ZENITH TELESCOPE.

By GEO. A. FARGIS, S. J.

The object of the present publication is to present some account of a practical method of utilizing the ordinary zenith telescope for determining latitudes by means of photography. This is the *third* photographic method tested at this Observatory, and, judging from its present effective working, it seems likely to gain a permanent footing. Preliminary experimental observations were made with an instrument of this kind in June, 1893, as described on page 59. The method and the results were satisfactory enough to justify the construction of an instrument of this class, especially adapted to photography. The realization of the plans were entrusted to Mr. G. N. Saegmuller. The completed instrument was mounted early in September, 1893, and the first latitude observations were made October 14th, 1893.

As may be seen from Plate VII, its general design is sufficiently familiar, with some few modifications suggested by experience gathered from the other photographic methods employed here. A description of these peculiarities, and of the practical working of this method may be of interest to those conversant with the methods previously described on these pages.

CHAPTER I.

DESCRIPTION OF THE INSTRUMENT.

1. The *object-glass* is of 6 inches aperture and 35 inches focal length. Stars of the sixth and seventh magnitudes are readily photographed, with an exposure of one second, even at the time of full moon. So many other trails appear on the plate during the short exposure necessary for a single latitude pair, that it has been found advisable to protect that part of the plate by the occulting bars, in the manner described on page 48.

2. The *eye-end* of the telescope has a graduated *draw-tube*, with rack and pinion motion, to facilitate the determination of the photographic focus. After this is once done, the tube is clamped in position.

The draw-tube, which is a little less than an inch in diameter, terminates in a *plate-holder*. This is a rectangular, light-tight, brass box, a little wider than the sensitive plates, which, in this instance, are $2\frac{1}{2}$ by $1\frac{1}{2}$ inches. The plate is held against the opening of the draw-tube by two springs fastened to the inner surface of the door of the box, which opens on hinges on the north or south side of the instrument. The plates are consequently inserted from the east or west. The door, when open, hangs downward by its own weight, and when the plate is in position it is fastened by means of a steel hook and eye. It is also arranged to carry a diagonal eye-piece, should occasion require.

3. There is only one *setting circle*, that for zenith distances. No azimuth circle is provided, as the instrument is not intended for extra-meridian observations.

The circle is 17 inches in diameter and reads directly to 5 minutes of arc, allowing exact setting to within one minute of arc by direct estimate, and without a vernier, a matter of some importance when time is limited. It is mounted opposite the telescope, and serves as part of the counterpoise. The horizontal ring at the base of the instrument carries two stops and adjusting screws. The vertical axis is also provided with a clamp and slow motion in azimuth.

The *slow motion* in altitude is at the base of the instrument, from either side of which it can be reached, by means of two handles connected with the clamp-arm by means of bevel-gears.

4. The instrument is furnished with a *striding-level*, resting permanently on the horizontal axis, and with two *latitude levels* attached close to the telescope. All three have air chambers, since the range of the telescope, within 30° zenith distance, is not wide enough to cause any unintentional change in the length of the bubbles.

5. The *photochronograph* is a double one, and, in the main, just as represented in Plate IV. The coils and occulting-bars are, however, fixed in one position, and the only adjusting screws are those for the armatures. The bars pass through a lateral opening in the draw-tube, but the photochronograph itself is attached to the main tube of the telescope. This opening is protected from moonlight, or reading-lights, by a cloth bag attached to this same tube, hanging loosely over the eye-end.

6. The instrument is mounted in the *room* described on page 46. As there stated, the box-shaped opening in the roof allows a sweep of 30° north and south of the zenith, but this has been extended so as to increase the range by 10° more on either side. The shutters of these openings are latticed, and serve as ventilators. The space under the floor is open on all sides to the weather, and the roof has been pierced for large ventilating shafts.

Very convenient *reading lamps* for the levels are attached to rods reaching down from the ceiling. These rods slide in brass tubes, and can be pushed up and down, and turned in any direction, strong springs holding them in any required position. Each terminates in a lamp box, thoroughly blackened, carrying an incandescent lamp which projects its rays through a horizontal tube upon the levels.

CHAPTER II.

ADJUSTMENT OF THE INSTRUMENT.

There are no wires in the focal plane of the instrument, and its adjustment in the meridian, in consequence, and the part played by the photochronograph for the same end, and for the purpose of a constant control over the adjustment when once made, present some features of interest.

1. In what follows we shall consider not the hour angle of a point, but the distance of the point from the meridian in equatorial seconds of time. If this quantity be called τ , any value of τ will represent the same number of revolutions of the measuring micrometer, without regard to the declination of the part of the sky to which the plate is exposed. The reduction to the meridian is then given by the expression

$$[6.7367]'' \tau^2 \tan \delta = 0''.00055 \tau^2 \tan \delta.$$

The greatest value of $\tan \delta$ for any stars observed here for latitude, is 3, so that the reduction is practically negligible even for $\tau = 2.5$, especially as $\tan \delta$ rarely has so large a value and for most stars is less than 1.3.

From the fact that there are *no fixed wires* in the field of view, and that the point on the plate which marks the meridian position of the star is determined by means of the photochronograph from the right ascension and the clock correction, it follows that in this method one is not obliged to take into account any instrumental error that would give a constant value of τ for all zenith distances; for if a point is in the meridian, or τ is zero at one zenith distance, such an error will not change the value of τ at other zenith distances, or the point will always be in the meridian.

Such is the case for the collimation error, which consequently vanishes in the present instance. The impossibility of correcting the collimation, since there is no fixed point to be adjusted, leads to the same conclusion.

The same holds, practically, for the level correction, within the 30° of zenith distance, north and south, within which the present series of observations is confined, unless it be unusually large. For the level error varies as the cosine of the zenith distance, and since $\cos 30^\circ = 0.866$, the level correction at this zenith distance differs from that at the zenith by only $\frac{2}{15}$ of its value, or, its values at $\zeta = 0^\circ$ and $\zeta = 30^\circ$, differ from that at $\zeta = 21^\circ$ by only $\frac{1}{15}$ of its value at this last. Hence, the level of the instrument need not be adjusted with extreme accuracy to render its effect insensible.

2. This applies properly to a single position of the instrument east or west of the vertical axis, but does not apply if the level errors differ for the two positions. Such a difference is caused by an error in the position of the vertical rotation axis, and since the two stars of a latitude pair are observed in the two different positions, the adjustment of the *vertical axis* needs constant care and control. Want of perpendicularity between the vertical and horizontal axis is of no moment, unless it be unreasonably large; since, although on reversing, the level error will change sign, the photographic plate is by the same reversal, changed end for end. This error may be permitted to run to a much greater value in the latitude observations than in the course of the various adjustments, since the two stars of a latitude pair are observed at nearly the same zenith distance. The level adjustments are made at the foot-screws of the stand, and at the **Y**'s of the horizontal axis by means of the standing level which remains always on the axis. The method of making the adjustments is obvious. In the present instrument both **Y**'s are fixed, and the adjustment is made by changing the surface of one of them.

3. Once these two sources of level error are sufficiently eliminated, the adjustment in *azimuth* is made by exposing plates under the photochronograph in either position of the instrument on pairs of stars, north and south of the zenith respectively, and adjusting the azimuth stops until the points of meridian passage on the two trails lie in the same vertical line.

This can be determined with much more than sufficient accuracy by micrometer measures of the plates, and, almost, if not quite sufficiently, by a simple inspection of the plates in the microscope, or with a hand magnifying glass.

4. A complete and continuous *control* can be exercised over the adjustment of the instrument by the use of the photochronograph for the latitude trails taken each night. For when the points of meridian passage are picked out by the help of the photochronographic register, for the purpose of measuring the difference of zenith distance, it becomes at once apparent whether the meridian points of the two trails are still on the same vertical line. If the divergence varies with the zenith distance of the pairs, one of the azimuth stops needs adjustment, but if it be constant, the vertical axis is out of perpendicular. It is obvious that this latter can also be controlled by means of the level always mounted on the horizontal axis.

5. The photographic *focus* is determined in the manner described on pp. 14 and 15, and the value of one division of the *micrometer screw* from each plate, as on pp. 28 and 51.

6. The *zero point* of the setting circle is determined photographically by noting the distances of the trails of a latitude pair from the inner edges of the occulting-bars, whose images are brought on the plates by fogging down the unprotected part, either by moonlight or by artificial light. A sufficient number of such plates are afforded on moonlight nights during the ordinary course of observation, to ensure perfect control of this point.

7. The *values* of a single division of the *latitude levels* can also be determined photographically.

The instrument is pointed on a star from the almanac, and the level bubbles, set some divisions to one side of the centre of the tubes. The levels are read about a minute before the meridian passage of the star which is tracing its path on the sensitive plate. About the moment of the meridian passage the instrument is moved in altitude by the slow motion, so as to bring the bubbles to the other side of the centre of the tubes and by almost the same amount. When the bubbles are at rest, the levels are again read and the temperature noted. The distance of the two parts of the star trail, expressed in revolutions of the micrometer screw and divided by the number of divisions the bubbles have moved, gives immediately the values for one division of each level in screw revolutions. One or two of these level plates form a regular part of each night's series of latitude observations.

In this fashion the values of screw and level, as well as their behaviors at the different seasons of the year and for all changes of temperature, may be accurately determined and discussed at any time from the series of plates.

CHAPTER III.

METHOD AND RESULTS.

1. An hour or so before the meridian passage of the first pair for the night's work, the large *shutters* of the latitude room are thrown open, and remain so during the night, except occasionally when the moon is near the meridian. In these instances they are closed for a moment to avoid danger of fogging while interchanging the sensitive plates. This could be obviated by the use of a plate-holder, but for many reasons of convenience it has been found preferable to use the naked plate.

2. The *level bubbles* are inspected and lengthened or shortened according to the temperature. The foot-screws of the instrument are then tested by several reversals of the instrument. The *occulting bars* of the photochronograph do not require attention, as they are permanently fixed in position, and have, together, a range of 30' of arc, or twice the width of the widest pair. The *hack clock* in the room is then corrected by the standard clock.

3. During the actual latitude work, the *photochronograph* can be employed in various ways, according to the actinic power of any given star. For example, it may be allowed to act during the whole exposure of the plate, so that the star trail is cut up into dots one second long and one second apart. This is found particularly convenient for stars between the 5th and 7th magnitudes, on which the working list is based. For brighter stars a one-tenth second exposure is used, every other second being cut out, and for stars farther north a single second exposure every five or ten seconds may be employed. This was the method followed with the Floating Zenith Telescope, and it obtains in the present instance. It obviously requires no wires in the field of view.

It might be thought that the shock of the occulting bars would affect the observations, but this is not borne out by experience, and besides did it occur, it would operate to prevent the sticking of the level bubbles.

The following are the principal *advantages* of the photochronograph in latitude observations:

a. Each plate supplies the data for a determination of the screw value of the micrometer microscope.

b. As the screw value is found from each plate it affords a means of judging whether there has been any distortion of the film during development. The direction in which the

screw value is measured is at right angles to that of the difference of zenith distance, but distortion of the film is not likely to be confined to only one of these directions. Besides, an additional check may be derived from an inspection of the parallelism of the trails, not only of the pair of latitude stars, but of the subsidiary trails which are invariably present on the plate.

c. If an ephemeris of the stars be made out, which can be readily done by graphical processes within a couple of tenths of a second, those points of the trails which coincide with the meridian passage can be easily distinguished, and the difference of zenith distance measured there.

4. It has been our custom to measure the difference of zenith distance of the pairs *only at the point* of the meridian passage, but it is evident, that it may also be measured at other points symmetrically placed with regard to the meridian. These points may be taken much nearer to the meridian than in visual observations, thus making the reduction to the meridian easier, and requiring less exactness in the adjustment of the instrument.

For, it is one of the advantages of the photographic method, that the observer is not hampered by being obliged to make the different micrometer settings so far apart as to give himself time to take and note the reading of the micrometer head. At the points, at which the micrometer settings are made, the wire may be set on the individual dots, or, on the general line of the trail in their neighborhood, or, which is perhaps best, on a small number of contiguous dots, e. g., the mean of an individual dot and one on either side.

5. In case it should happen that one of the stars of a pair, suitable in every other respect, be too feeble in actinic power to afford a good trail when broken up into second dots, yet strong enough to give a good continuous trail, the remedy is obvious and simple. The clock is switched out of circuit and the current switched on, thus holding the occulting bars open, and at the moment of meridian passage the current is broken for one second, shutting the bars and marking the point as intelligibly as in the other cases.

6. In practice it has been found that the working of this instrument requires only a few seconds greater *interval* between successive pairs or components of pairs than is necessary to insure accurate level readings and to set on the next pair. It follows that it does much quicker work than the Floating Zenith Telescope, but in this respect at least it ranks below the Reflecting Zenith Telescope, for which the meridian passages of the components of a pair may be simultaneous. In the present case two minutes between pairs, and one between components, suffice, when necessary. The working list contains 96 pairs.

Besides, fully 50 per cent. of the plates present other easily identified trails, within the limits of 15' zenith distance. These trails furnish additional pairs and additional values of latitude, though not always independently of each other. One such plate, for example, gives three additional trails, though commonly there is but one. The various combinations of these trails will furnish extra pairs at the rate of two or three an hour.

7. The *micrometer microscope* has been somewhat improved by the introduction of double wires and an eye-piece with lateral motion. A new micrometer is now being suitably mounted for this work.

8. A preliminary determination of the latitude of this Observatory, by means of the Photographic Zenith Telescope, as resulting from the observation of 10 pairs of stars, observed each 10 times, is

$$\delta = 38^{\circ} 54' 26.''01$$

Thus the latitude of this Observatory rests on the following determinations, which are not based, however, on declinations of the same system :

Time.	Latitude.	Instrument.	Observer.
1846, Sept. 16–Nov. 30	38° 54' 26.''07	Meridian Circle.	Curley.
1892, May 3–9	26.''02	Floating Zenith Telescope.	Fargis.
1893, April 3–27	25.''84	Reflecting Zenith Telescope.	Algué.
1893, Oct. 14–Dec. 27	26.''01	Photographic Zenith Telescope.	Fargis.

GEORGETOWN COLLEGE OBSERVATORY.

THE PHOTOCRONOGRAPH

APPLIED TO MEASURES OF

DOUBLE STARS AND PLANETS.

STORMONT & JACKSON,
PRINTERS,
WASHINGTON, D. C.
1894.

Plate VIII.



CASTOR. JAN. 1st, 1894 X 3.

PREFACE.

The application of the Photochronograph to measures of double stars was first made, at this Observatory, in 1891.

A preliminary account of the method was given in the *Astronomische Nachrichten* (No. 3058), and the hope was expressed that some large photographic equatorial would be devoted to this line of work.

In the meantime this Observatory received a donation for a twelve-inch equatorial, and one of the first tests to which the instrument was subjected, after construction, was the photographing of double stars. The results of our experiments are set forth in the following pages.

The photographs were taken by Prof. G. A. Fargis, and the micrometer measures of the plates were also made by him.

It is our intention to continue these observations, and especially to determine the positions of Jupiter's satellites at every opposition of the planet.

GEORGETOWN COLLEGE OBSERVATORY, *January* 6, 1894.

J. G. HAGEN, S. J.

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THE PHOTOCRONOGRAPH

APPLIED TO MEASURES OF

DOUBLE STARS AND PLANETS.

BY GEO. A. FARGIS, S. J.

PART I.

DOUBLE STARS.

CHAPTER I.

PRELIMINARY EXPERIMENTS.

1. The first photograph of a double star, by means of the Photochronograph, taken at this Observatory, dates as far back as May 9, 1891. On that day a negative of the transit of ζ Ursae Majoris, taken with the $4\frac{1}{2}$ inch Ertel Transit Instrument, exhibited also the south following companion, and showed the feasibility of measuring the position angle and distance.

This photographic image measured 19 mm. in length, and represented an interval of four minutes of time. Hence, it presented a row of $4 \times 56 = 224$ instantaneous photographs of each of the two companions, with an interruption of 3 seconds between each minute, and of 1 second at each half minute, at which points there are no images. These vacant spaces are required to identify corresponding images of the two companions. Only about one-third of these images were selected for measurement, and they were divided into three groups, each con-

taining 24 photographs of the companions. Position angles and distances, as well as the differences of R. A. and declination were measured, and a description of the method and its results were published in 1891 (*Astr. Nachr.*, No. 3058, p. 177):

2. In the same article the previous experiments of Bond (*Astr. Nachr.*, Nos. 1129 and 1158), were mentioned, and attention was called to the differences between the various methods of double star observations, viz.: the visual method, the time exposures in the Bond photographs, and the instantaneous images from the photochronograph.

In the visual method, the observer is obliged to make a mental estimate of the mean position of two stars, which are flickering and boiling. On a long exposure plate, which follows the path of the object by means of the driving clock, the disturbed images are superposed, and form, as Bond expresses it, "the self-registered mean effect of all the disturbances of the image during the exposure of the plate" (A. N. 1129, p. 14). These two methods agree, however, in this, that they afford no means of measuring the quantity of these disturbances, whether seen successively, as in visual observations, or simultaneously, as in the photographic method.

This is done in the photochronographic method, where the instrument is clamped in R. A., and a series of instantaneous photographs is obtained on the plate. The measures of these images furnish not only a *mean* result, free from atmospheric disturbances, as in the case of the two preceding methods, but give besides a faithful account of the disturbances themselves.

Attention was also called to several other advantages, especially the elimination of *personal* errors, mentioned by Bond, and also of various *instrumental* errors. As an instance of the latter, it may be remarked that, since the telescope is clamped during the exposure of the plate, there are no errors due to the driving-clock or to the misplacing of the polar axis.

As regards *personal* errors, it is more accurate to say that they are of a different kind, rather than that they do not exist; for, evidently, there must be an observer, here as elsewhere, and, consequently, errors of setting, seeing and estimating, both constant and accidental, must necessarily occur. But the great and conspicuous advantage, outweighing all the others, is the *feasibility* of, first, *re-examining each plate*, and second, *taking the screw value directly from it*. Everyone knows how difficult it is to explain and weigh the discrepancies which occur in every series of observations, and to recompute old observations, owing to lack of knowledge of the instrumental constants, and especially of the screw-value. In the photochronographic method, each and every doubtful figure can be investigated and checked by re-examining the plate, and the combined results recomputed; for the plate is free from all

instrumental errors, except those due to the sensitive plate, and it holds a permanent record of the screw-value.

3. Further experiments were deferred until March, 1893, when the 12-inch equatorial was ready for work.

The first thing to start with was a *suitable working-list of double stars*. The difficulties of this selection depended on various elements, such as the aperture and focal length of the telescope, the amount of absorption of light by the three lenses, and their more or less perfect correction for actinic rays, the colors, photographic magnitudes and distances of the components, the linear velocities of their images on the sensitive plate, the time of exposure, the sensitiveness of the plates, and the transparency of the atmosphere at any given time.

There are empirical formulae which give the magnitudes of stars, that can be photographed by a given instrument, when the aperture, focal length, and time of exposure are known. But as they obviously account for only three out of the many elements just mentioned, the only practical way of making a working-list for this method, was that of actual trial.

The result of these experiments, carried on at intervals during a year, is the enunciation of the following general principles, which serve as guides for the profitable working of this equatorial in conjunction with the photochronograph.

(a). Stars of *sixth visual magnitude*, and *distances of 3 seconds of arc*, as a rule, limit the instrumental capacity for producing measurable images.

(b). The *amount of exposure* must be studied for each particular double star, and no general rule can be laid down. In the present case it varies from considerably less than one-tenth of a second up to a whole second, according to the actinic power of the components, their distance, declination, and position angle. For example, the fifth visual magnitude usually requires a full second exposure, but if the components are only 3" apart, these images will overlap by halation. Equatorial stars give, in general, elongated images, while those nearer the pole give circular ones, under all circumstances. So that, on the whole, it is easier to obtain good pictures of faint double stars, near the pole, than near the equator.

(c). The *components* should not differ by more than two magnitudes, and the more nearly they are equal the better the results. But in this connection, it must be remarked, that pairs like Castor, and especially γ Leonis, give wonderfully sharp and well separated images of the smaller component, when the magnitudes are reduced one-half, in the usual way. It would seem, from plates actually on hand, that the best results are to be obtained, with the smallest magnitude consistent with sufficiently intense images. This will probably increase the present list by several pairs, and very considerably improves those already available.

(d). *Want of transparency in the sky*, even if directly undetectable, usually exerts a great influence on the actinic power of a star. Under apparently precisely the same conditions of sky, plate, exposure, development, etc., a star will give no results for a long series of photographs, and then, unexpectedly, will yield an almost perfect negative. Partly owing to this uncertainty, six or eight plates are always exposed for any given set of conditions. The *moon* does not seem to interfere with photographic work, providing her light does not shine directly into the telescope.

The exceptions to the above general rules, are numerous and very puzzling, and go to show that the only reliable guide in the whole matter is the evidence of the photographic plate itself.

It is not surprising, therefore, if but comparatively few binaries are found to fall within the scope of this method, under existing instrumental conditions. These preliminary experiments have given only 15 suitable stars from the "Handbook of Double Stars." There are five or six more, however, that will be included in the near future. The list might be largely extended by the addition of all optical doubles, above fifth magnitude and 3" distance. Observations of these *apparent double stars* are by no means useless, since they may serve to determine the parallax of the proper motion of one of the companions, or to give standard distances in various parts of the sky for determining screw values. As examples, two stars not given in the "Handbook of Double Stars," have been taken, viz.: β Cygni and companion, and Mizar with Alcor.

4. The following table presents the stars observed by this method. They have all been known and observed for over a hundred years. The visual magnitudes have been taken from the "Handbook of Double Stars," except those of ϵ^1 and ϵ^2 Lyrae, which were taken from the B D.

The numbers with asterisks indicate stars, which were observed by mutual agreement, by Bessel and W. Struve, between the years 1825 and 1832, at Königsberg and Dorpat, in order to compare the performances of the heliometer and equatorial, both by Fraunhofer. (See Bessel's Abh. B. II, pp. 285-291.)

It may be remarked in passing, that this series of experiments includes 663 photographs, taken during forty nights, and over fifty thousand micrometer settings.

TABLE I.

No.	Name.	Place, 1880.		Visual Magnitudes.	Distance.	Exposure.	Observed since
1	ϕ^1 Piscium.	0 ^h 59 ^m	+20° 50'	5, 5	30'' 0	1 ^s 0	1779, H ₁ .
2*	ζ Piscium.	1 7.5	+ 6 56	4.2, 5.3	23.4	1.0	1781, H ₁ .
3*	γ Arietis.	1 47	+18 42	4, 4	8.4	0.1	1780, H ₁ .
4*	γ Andromedae.	1 56.5	+41 46	3, 5	10.0	0.1	1777, Mayer.
5	β^2 Eridani.	3 48.2	— 3 19	4, 6	6.5	1.0	1781, H ₁ .
6*	α Geminorum.	7 27	+32 9	3, 4	5.6	0.1	1718, Bradley.
7*	γ Leonis.	10 13.4	+20 27	2, 3	3.2	0.1	1782, H ₁ .
8*	γ Virginis.	12 35.6	— 0 47	3, 3	5.6	0.1	1720, Cassini.
9*	ζ Ursae Maj.	13 19.1	+55 33	2, 4	14.3	0.1	1755, Bradley.
10	δ Serpentis.	15 29.1	+10 56	3, 4	3.4	0.1	1782, H ₁ .
11	ρ Herculis.	17 19.5	+37 15	4, 5	3.3	0.1	1781, H ₁ .
12	$\epsilon^1 \epsilon^2$ Lyrae.	18 40.4	+39 31	4.3, 4.6	208.6	1.0	1779, H ₁ .
13*	γ Delphini.	20 41.8	+15 42	4, 5	10.8	0.1	1755, Bradley.
14	ξ Cephei.	22 0.3	+64 2	5, 7	6.5	0.5	1780, H ₁ .
15*	ζ Aquarii.	22 22.6	— 0 38	4, 4	3.0	0.1	1777, Mayer.

CHAPTER II.

THE TELESCOPE.

The instrument usually employed for these observations is the 12-inch equatorial. Occasionally, however, the 4½-inch transit, described on page 9, and the 6-inch Zenith Telescope have been used with effect. The mounting of the equatorial was made in Washington, by Mr. G. N. Saegmuller, and the objective by Mr. John Clacey. The working of the instrument is very satisfactory, and presents some features deserving of special mention.

1. The telescope is provided with two sets of circles, one with fine graduation on silver, the other with coarse white lines and figures on the black circumference. Both are wired for electrical illumination. Up to the present, these have not been used, as the maker has furnished a third means of setting the instrument. There are *two dials* on the pier, just above the two hand wheels for setting; the one for declinations, the other for right ascensions. Each dial has a large hand, which is geared with one of the rods, through which the motion of the hand-setting wheels is communicated to the telescope, and hence moves with it. The declination dial is fixed in its box. The right ascension dial is driven by clock-work, so that the movable hand gives the right ascension at once, while a fixed pin on the circumference of the box shows the sidereal time.

The dials are graduated to one degree and four minutes respectively. It is easy to estimate tenths of the divisions, which is sufficient to bring any object into the field of the 4-inch finder. The position of the dials before the eye, and the fact that right ascensions can be set directly, make it easy to set quickly, the setting in both co-ordinates taking less than half a minute of time.

2. The next thing to be mentioned is the attachment of the *photographic corrector*, a third lens of 12-inch aperture. Its cell is fastened to that of the visual objective by three screw-bolts symmetrically placed around the circumference and by a hinge, on which it turns three-quarters of a revolution to the outside of the telescope tube, where it is secured to a projecting fork by a T-shaped pin and thumb-screw. It shortens the visual focus ten inches. The shortening and lengthening of the tube for visual or photographic work is done here, and not at the eye-end. The cell of the object glass is fastened to a draw-tube sliding on three steel rods. The weight of the eye-piece, which is removed when the tube is pushed in to shorten the focus for photographic work, compensates for the loss at the object end and

dispenses with all interchange of balancing weights in declination. According to the present plan of work, the photographic corrector is placed in position at each lunation near the beginning of the first quarter and removed about the last. Near the period of new moon the equatorial is used for visual work.

3. The *photochronograph* used for the work on double stars and planets is either the single one, as represented on Plate I., or the double, as on Plate IV. The first answers admirably for nearly all double stars; whereas for the planets, the second is preferable on account of the wide range of the occulting-bars. At the eye-end there is a tube 5 inches in diameter, which is inserted in the draw-tube of the telescope in place of the eye-piece used for visual observations. This tube carries the clamp-ring for the photochronographs and a low power eye-piece for adjusting the object exactly in position under the occulting-bar.

The *Cramer sensitive plates* are of the same size as those used in transit and latitude observations, *i. e.*, $1\frac{1}{2}$ by $2\frac{1}{2}$ inches. They are used without a plate-holder, and are simply placed against the end of the tube mentioned above, and held there by a spring.

4. The *electric wires* from the switch-board in the clock-room terminate in binding-posts on a wooden block fixed to the bottom of the equatorial pier. These posts are lettered similarly to the other termini of these wires on the switchboard. They are connected with the eye-end of the telescope by flexible wires.

One of these wires is marked **D** (*dome wire*), and it puts any instrument, clock or electric battery of the Observatory, at the service of the observer; this is directly attached to the photochronograph, and passes through a switch, by which arbitrary signals can be made. Another wire terminates in a two-point switch at the eye-end of the telescope, and enables the observer to use any one of four clocks at will. These clocks have different automatic electric break-circuits, and their use will appear from what follows.

The *dome* is lighted by 20-candle power incandescent lamps, both fixed and portable, one being enclosed in a lantern box of ruby glass.

The *objectives, both visual and photographic*, were furnished by Mr. Clacey, now of Washington, and they are, in all respects, satisfactory. The photochronographic method of double star observations seems to be one of the severest tests to which a photographic lens can be submitted, as will appear on consulting Table I., p. 103. Doubtless it requires considerable light-gathering power for any telescope to photograph a fifth magnitude star with a one-tenth second exposure. But this point becomes still more noteworthy, in the present instance, when it is considered that the ratio between focal length and aperture in this instrument is as large as 15, which is greater than that of the telescopes used for the International Photographic

Charts: and that, besides, since the telescope is clamped, the star always makes a trail on the sensitive plate, no matter how short the exposure. From the same Table I., p. 103, it is also evident that for a star like γ Leonis, the images of the two companions, of second and third magnitude respectively, must be less than 3 seconds of arc in diameter. Under first-class conditions, *i. e.*, when the lenses have cooled down to the proper temperature, the atmosphere being transparent and calm, and the sensitive plate sufficiently responsive, these images appear as perfectly round dots, clearly separated from each other. It is only under such conditions, which are not always at command, that an objective can show its true working powers. In the course of these experiments, it became obvious that the Clacey objective was doing extremely fine work, and it is a pleasure to have the present opportunity of expressing our complete satisfaction with its performance.

CHAPTER III.

INDIVIDUAL RESULTS OF DOUBLE-STAR MEASURES.

The plates were measured with the micrometer microscope used for latitude and transit observations. As a rule, only one careful setting for distance and angle was made on each pair of images. As the construction of the micrometer did not permit the measurement of double distances, the figures given are the differences between two single settings, one on each of the two components.

In *measuring the angles*, the fixed wire, which is perpendicular to the movable one, was first set on the row of images of either of the companions. This setting was generally made ten times. The micrometer-box was then turned, and the double movable wire set on successive pairs of corresponding images of the companions by turning the box and advancing the double wire by the micrometer screw. The wire was thus set on from fifteen to twenty pairs, but only once on each pair. The plate was then shifted, so as to bring other images into the field of view, and the angles measured from another group. Each plate afforded at least three groups, and, in every case, the wire was thrown out of position between each pair of images. A single movable wire was used for all measures of the position angles of ζ Urs. Maj., α Gemin., γ Leonis, and γ Virginis, as the double wire had not yet been inserted in the micrometer.

The angle once determined, the micrometer box was set for the measures of *distances*. Only one setting was made on each dot, and the distance of the two companions is simply the difference of two settings.

Then, the differences of right ascension were measured in a manner similar to that used for transit observations (page 25), and, finally, the differences in declination were taken after the method adopted for latitude observations (page 52).

Only the progressive errors of the screw were applied when necessary. The periodic errors were neglected, as they were eliminated, at least in the distances, owing to the large number of images measured.

The screw values may be determined for each plate by the method already described. In the reduction, however, the following mean values have been applied :

R = 6'' 606.....	for the 12-inch Equatorial.
R = 29'' 786.....	“ 6 “ Zenith Telescope.
R = 14'' 017.....	“ 4.5 “ Transit Instrument.

The focal lengths of these three instruments are respectively about 15 ft., 3 ft. and $7\frac{1}{2}$ ft.

1. In the following table, p= the position angle, s= the distance, and n= the number of images measured on each plate. $\Delta\rho$ is the correction for refraction.

TABLE II.

1. ψ^1 *Piscium*.

Plate.	Date.	Sid. Time.	p	n	s	n	Instrument.
489	1893.851	0 ^h .3	159° 91	60	30'' 06	60	12-inch.
490	"	0 .4	.89	"	29.93	"	"
491	"	0 .5	.94	"	30.03	"	"
1893.851			159.91 $\Delta\rho=0.00$		30.01 $\Delta\rho=+0.01$		
2. ζ <i>Piscium</i> .							
535	1893.862	1.5	63.40	60	23.31	48	12-inch.
536	"	1.5	.39	"	23.35	"	"
538	"	1.6	.40	"	23.54	"	"
1893.862			63.40 $\Delta\rho=0.00$		23.40 $\Delta\rho=+0.01$		
3. γ <i>Arietis</i> .							
516	1893.862	23.7	359.27	45	8.41	30	12-inch.
518	"	23.8	.22	"	8.49	"	"
520	"	23.8	.22	"	8.35	"	"
1893.862			359.24		8.42		
4. γ <i>Andromedae</i> .							
521	1893.862	0.3	64.08	60	10.03	60	12-inch.
523	"	0.3	.22	"	9.90	"	"
526	"	0.4	.23	"	9.91	"	"
1893.862			64.18 $\Delta\rho=-0.01$		9.95 $\Delta\rho=0.00$		

5. 32 *Eridani*.

Plate.	Date.	Sid. Time.	p	n	s	n	Instrument.
542	1893.862	2 ^h 7	346° 53	27	6''45	60	12-inch.
544	"	2.8	.43	"	6.47	"	"
545	"	2.9	.83	"	6.57	59	"
1893.862.			346.60		6.50		

6. α *Geminorum* (*Castor*.)

133	1893.254	9.7	222.85	112	5.57	80	12-inch.
134	"	9.7	222.95	83	5.58	63	"
135	"	9.7	222.91	85	5.58	63	"
241	1893.326	11.7	223.29	83	5.82	63	"
242	"	11.7	223.19	125	5.67	63	"
243	"	11.8	222.99	112	5.67	63	"
245	"	11.9	223.11	128	5.61	60	"
246	"	11.9	223.02	141	5.63	63	"
247	"	12.0	222.99	124	5.67	63	"
1893.183			223.03		5.63		

7. γ *Leonis*.

142	1893.260	9.2	114.92	27	3.83	32	12-inch.
143	"	9.3	.96	27	3.63	48	"
144	"	9.3	.92	41	3.44	"	"
145	"	9.4	.96	70	3.43	"	"
147	"	9.5	.97	100	3.37	"	"
257	1893.350	11.5	.94	71	3.50	"	"
258	"	11.6	.94	67	3.44	"	"
259	"	11.6	.98	70	3.57	"	"
307	1893.356	12.0	.98	81	3.50	"	"
308	"	12.0	.90	100	3.43	"	"
310	"	12.9	.96	97	3.50	"	"
311	"	12.9	.90	83	3.57	"	"
312	"	13.0	.96	68	3.63	"	"
1893.318			114.95		3.53		

DOUBLE STARS AND PLANETS.

8. γ Virginis.

Plate.	Date.	Sid. Time.	p	n	s	n	Instrument.
2747	1892.397	12 ^h 6	150°.94	101	5''37	83	4.5 inch.
2835	.408	12.6	151.03	112	5.52	107	"
2872	.413	12.6	151.00	140	5.56	110	"
157	1893.260	10.8	148.99	69	5.46	57	12-inch.
158	"	10.9	149.03	82	5.59	63	"
159	"	10.9	148.96	55	5.58	63	"
303	1893.356	11.5	148.99	95	5.57	60	"
304	"	11.5	149.05	95	5.62	61	"
1892.406			150.99		5.49		4.5-inch.
1893.298			149.01		5.56		12-inch.

9. ζ Ursae Majoris (Mizar.)

2432	1892.242	13.3	148.12	187	14.20	112	4.5-inch.
2481	.302	13.3	.05	187	14.12	102	"
2775	.400	13.3	.03	195	14.18	112	"
94	1893.222	10.0	147.99	115	14.29	112	12-inch.
95	"	10.0	147.96	92	14.24	112	"
136	1893.254	10.5	148.03	69	14.25	72	"
137	"	10.5	148.08	62	14.38	68	"
138	"	10.6	147.90	55	14.45	55	"
139	"	10.6	148.11	74	14.40	82	"
140	"	10.7	147.97	74	14.36	84	"
141	"	10.7	148.02	81	14.41	89	"
1892.315			148.07		14.17		4.5-inch.
1893.246			$\Delta\rho=0.00$ 148.01 +0.01		$\Delta\rho=0.00$ 14.34 $\Delta\rho=0.00$		12-inch.

10. δ Serpentis.

328	1893.356	15.5	185.89	51	3.39	56	12-inch.
329	"	15.6	.92	48	3.54	60	"
330	"	15.6	.87	48	3.34	55	"
1893.356			185.89		3.43		

11. ρ *Herculis*.

Plate.	Date.	Sid. Time.	p	n	s	n	Instrument.
418	1893.770	21 ^h 8	313° 62	69	3'' 69	72	12-inch.
421	"	22.0	.53	78	3.69	"	"
422	"	22.0	.46	75	3.69	"	"
1893.770			313.54 $\Delta\rho = -0.02$		3.69 $\Delta\rho = 0.00$		

12. $\epsilon^1\epsilon^2$ *Lyrae*.

	1893.526	18.7	172.48 $\Delta\rho = 0.00$	240	208.59 $\Delta\rho = +0.06$	240	6-inch.
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13. γ *Delphini*.

433	1893.770	22.7	271.14	20	10.79	17	12-inch.
434	"	22.8	271.08	"	11.00	19	"
435	"	22.8	270.93	"	10.73	20	"
1893.770			271.05 $\Delta\rho = -0.01$		10.84 $\Delta\rho = 0.00$		

14. ξ *Cephei*.

441	1893.770	23.5	283.43	28	5.86	25	12-inch.
443	"	23.6	282.86	35	5.84	40	"
471	1893.852	23.1	282.53	40	5.82	40	"
1893.797			282.94 $\Delta\rho = -0.01$		5.84 $\Delta\rho = 0.00$		

15. ζ *Aquarii*.

480	1893.852	23.7	325.67	60	2.87	60	12-inch.
481	"	23.8	.72	"	2.99	"	"
482	"	23 8	.68	"	2.97	59	"
1893.852			325.69 $\Delta\rho + 0.01$		2.94 $\Delta\rho = 0.00$		12.inch.

2. Besides these, two other double stars, β Cygni and Mizar with Alcor, have been observed.

If β Cygni and its companion do not form a binary system, and do not mutually attract each other, they must be a great distance apart, and consequently have a different parallax. Thus, whether the system be binary or merely optical, the measures of the relative positions of the two stars are somewhat interesting; the more so as the parallax of β has of late been the subject of some investigation and discussion.

The other pair, Mizar and Alcor, is visible the greater part of the year, and seems to present a convenient means for determining the value of a revolution of the micrometer screw, for visual observations, in the same way as certain arcs in Perseus, Praesepe and the Pleiades. The following are the results :

16. β Cygni and its companion,

(photographed with the 12-inch equatorial, and with one-tenth second exposure.)

Plate.	Date.	Sid. Time.	p	n	s	n
468	1893.852	22 ^h 6	55° 42	60	34'' 43	51
469	"	22.6	.44	"	.40	50
470	"	22.7	.43	"	.43	51
1893.852			55.43 $\Delta p = -0.01$		34.42 $\Delta p = +0.02$	

17. Alcor and principal star of Mizar,

(photographed with the 6-inch zenith telescope and one second exposure.)

Plate.	Date.	Sid. Time.	$\Delta \delta$	n	p	n	s	n
292	1893.353	13 ^h 3	3' 39'' 82 $\Delta p = +0.07$	25	71° 94 $\Delta p = 0.00$	120	11' 47'' 18 $\Delta p = +0'' 20$	216

In this table $\Delta \delta$ means the difference in declination. The following are the probable errors of these quantities, computed from the discordance of the separate measures :

for $\Delta \delta$: $\pm 0''.05$, for p : $\pm 0''.02$, for s : $\pm 0''.08$.

CHAPTER IV.

DISCUSSION OF THE RESULTS.

1. Table III gives the differences $\Delta\alpha$ and $\Delta\delta$ of the two companions, expressed in revolutions of the micrometer screw; then the final results of p and s , reproduced from Table II (omitting $\Delta\rho$), and finally the values p' , s' , of the position angles and distances computed from the columns $\Delta\alpha$ and $\Delta\delta$.

The comparison was very instructive, as a check on all the measures, and brought out strikingly the great advantage of the photographic method, viz: the feasibility of re-examining the measures, and repeating them, independently and comparatively, until all apparent discrepancies are traced back to their source.

2. The probable errors of a *single image* affords another means of estimating the value of this method. They are presented in Table IV, page 115.

Owing to the great number of images on each plate, and, to the fact that the single images are affected by the actual atmospheric disturbances, the single measures were made somewhat rapidly, so that only the *mean result of the measures of a group of images*, would appear to be comparable with a single deliberate measure in the visual method. Perhaps the *time* spent in securing one complete visual observation, might afford an approximate idea, as to how many measured photographic images, should be considered equivalent. To measure the position angles and distances from a plate giving about 60 good images of the two components, requires on an average three-quarters of an hour, or say, *about fifteen minutes for one group of images simultaneously visible in the field of the microscope*, or rather less than one minute for the position angle and distance of each image. As a matter of fact, the setting of the fixed wire in the micrometer, parallel to the row of images for the angles, and in the direction of the two components for distances, which consumes most time, is done *once* for all the images of a group, and then the setting of the movable double wire on the single images proceeds very quickly.

However, in order that the reader may form his own judgment, he will find in the following table the probable errors of the measures of a *single image*, for angle and distance. The stars are arranged according to the distance of the companions. All the numbers refer to the 12-inch equatorial, except in the cases of ζ Urs. Maj., and γ Virginis, where the lower numbers refer to the 4.5-inch transit instrument.

In this table σ and π denote the probable errors of the distance and the position angle. It also contains the probable errors of W. and O. Struve from the Observations de Pulkova, vol. IX, p. 152. The numbers for distance given by Σ have been multiplied by $1/\sqrt{2}$, and those of $O\Sigma$, by 2, since they measured one and two double distances respectively. Similarly Σ made two observations for position angle, $O\Sigma$, made three, so that in the present case the multipliers $1/\sqrt{2}$ and $1/\sqrt{3}$ were used. In the headings of the columns, after the letters σ and π , the reader will find annexed the letters P, Σ , $O\Sigma$ in order to distinguish the probable errors of the photographic method from those of the two Struves.

TABLE III.

No.	Name.	$\Delta\alpha$	$\Delta\delta$	p	p'	s	s'	$\sin(p-p')s$	s-s'
1	ζ^1 Piscium.	1 ^R 585	4 ^R 253	159° 91	159° 57	30'' 01	29'' 98	+0'' 18	+0'' 03
2	ζ Piscium.	3.188	1.560	63.40	63.93	23.40	23.45	—0.22	—0.05
3	γ Arietis.	0.025	1.253	359.24	358.86	8.42	8.28	+0.06	+0.14
4	γ Andromedae.	1.352	0.607	64.18	65.82	9.95	9.79	—0.29	+0.16
5	β^2 Eridani.	0.227	0.982	346.60	346.98	6.50	6.66	—0.04	—0.16
6	α Geminorum.	0.632	0.634	223.03	224.91	5.63	5.91	—0.18	—0.28
7	γ Leonis.	0.478	0.251	114.95	117.60	3.53	3.57	—0.16	—0.04
8	γ Virginis.	0.401	0.743	149.01	151.65	5.56	5.58	—0.26	—0.02
9	ζ Ursae Maj.	1.116	1.866	148.01	149.12	14.34	14.36	—0.28	—0.02
10	δ Serpentis.	0.090	0.544	185.89	189.39	3.43	3.64	—0.21	—0.21
11	ρ Herculis.	0.412	0.379	313.54	312.61	3.69	3.61	+0.06	+0.08
12	$\varepsilon^1 \varepsilon^2$ Lyrae.	0.910	6.939	172.48	172.53	208.59	208.45	—0.18	+0.14
13	γ Delphini.	1.660	0.030	271.05	271.04	10.84	10.97	0.00	—0.13
14	ξ Cephei.	0.874	0.224	282.94	284.38	5.84	5.96	—0.15	—0.12
15	ζ Aquarii.	0.274	0.373	325.69	323.70	2.95	3.06	+0.10	—0.11
16	β Cygni.	4.285	2.956	55.43	55.40	34.42	34.39	+0.02	+0.03

TABLE IV.
PROBABLE ERRORS OF SINGLE MEASURES.

Name.	Distance.					Position Angle.					
	s.	σ P.	s.	$1/\sqrt{2}\sigma\Sigma$.	$2\sigma\theta\Sigma$.	π P.		$1/\sqrt{2}\pi\Sigma$.		$1/\sqrt{3}\pi\theta\Sigma$.	
β Cygni.	34''4	$\pm 0''28$				$\pm 0^\circ 40$	$\pm 0''240$				
ϕ^1 Piscium.	30.0	0.25	28''	$\pm 0''279$	$\pm 0''242$	0.26	0.136	$\pm 0^\circ 57$	$\pm 0''281$	$\pm 0^\circ 56$	$\pm 0''276$
ζ Piscium.	23.4	0.40	20	0.272	0.250	0.45	0.184	0.59	0.211	0.68	0.243
ζ Ursae Maj.	14.3	0.34	14	0.264	0.264	0.42	0.105	0.83	0.206	1.23	0.303
“		0.59				0.34	0.085				
γ Delphini.	10.8	0.36				0.37	0.070				
γ Andromedae.	10.0	0.30	10	0.254	0.270	0.30	0.052	1.06	0.190	1.68	0.300
γ Arietis.	8.4	0.24				0.18	0.026				
ξ Cephei.	6.5	0.31				0.39	0.044				
β^2 Eridani.	6.5	0.27	6	0.208	0.188	0.15	0.017	1.53	0.168	1.78	0.197
α Geminorum.	5.6	0.22				0.45	0.089				
γ Virginis.	5.6	0.30				0.21	0.020				
“		0.67				0.23	0.022				
δ Serpentis.	3.4	0.38				0.35	0.021				
ρ Herculis.	3.3	0.37	3	0.162	0.172	0.67	0.038	1.97	0.109	2.42	0.133
γ Leonis.	3.2	0.64				0.18	0.010				
ζ Aquarii.	3.0	0.20				0.84	0.043				

The *change of distance* does not seem to introduce any certain change in the probable error, which seems to depend entirely on the error *in setting on a single image of a star*. In the photographic transit observations, the probable error of a single setting on a dot, is $\pm 0^R034$ revolutions of the micrometer screw, for good plates, and $\pm 0^R036$ for all the plates. Hence, the probable error of a single distance would be $\pm 0^R048$ and $\pm 0^R050$, respectively. The mean value of σ in the preceding table, expressed in revolutions, is $\pm 0^R050$, which is the same error.

In concluding, it seems proper to insist on the main advantage of the photographic method. This lies, not so much in the elimination of accidental errors from single observations, resulting in a diminution of the probable error, as in the permanent record of the star images, and the feasibility of remeasuring them under various conditions. It would, therefore, appear that it is peculiarly competent to deal with systematic errors of measurement, which affect results so much more seriously than accidental ones.

PART II.

PLANETS AND SATELLITES.

In the ordinary method of photographing the planets, an enlarging lens is used in conjunction with the objective. This can be profitably done, since the large amount of light given out by these bodies is amply sufficient to produce a good picture, even when spread over a large area of plate. As these enlarged photographs are not instantaneous, the driving-clock must be employed, and if more than one image on the same plate be required, the telescope must be moved by the slow-motion screws. The method now to be proposed differs in three points. *First*, the successive exposures are made at intervals which are regular and as short as possible, consistently with the actinic power of the object; *secondly*, there is no enlarging lens, and *thirdly*, the telescope remains stationary during the time of exposure. The occulting-bars of the photochronograph, which are moved either automatically by a clock, or by means of a key in the electric circuit, produce a series of nearly instantaneous images, at regular intervals, indicating the direction of the diurnal motion. The measuring of the plates obtained by these two different methods, differs accordingly. The enlarged photographs can be measured directly by means of a scale, while the primary images must be magnified by the microscope. For the topographical study of a planetary surface, the enlarged photographs are preferable, since the primary images are necessarily wanting in fine detail. But, where detail is of no importance, and where centres of images for position angles and distances, and for accurate orientation in regard to the celestial sphere, are the essential points, the second method possesses some decided advantages.

Experiments have, therefore, been made along various lines, according to these principles, and a brief account of them, with some of the results, may prove useful for future investigations.

CHAPTER I.

CONJUNCTIONS.

A near approach of planets and fixed stars can be photographed and measured exactly as a double star. The extent to which this can be practically utilized, depends, of course, on the aperture and focal length of the instrument employed. This limits the work at this Observatory to the brighter planets, and stars not lower than 5.5 magnitude.

So far, only one opportunity of testing this method has presented itself, viz.: the approach of Saturn to the double star γ *Virginis*, on April 8th, 1893. Unfortunately, the double photochronograph had not yet been adapted to the equatorial, and the single one, then being used for double star work, had not range enough to occult planet and star simultaneously. So that the planet gave a series of instantaneous images, while the double star gave merely a continuous double trail. Hence, the only measurable element was the difference of declination.

Five plates were exposed, each of which gives three images of Saturn, one-half a minute of time apart. The following are the results:

TABLE V.

DIFFERENCE OF DECLINATION: SATURN— γ^2 VIRGINIS, APRIL 8, 1893.

Plate.	Sid. Time.	Greenwich M. T.	$\Delta\delta$	
a	10 ^h 52 ^m .2	14 ^h 50 ^m .2	46 ^R .545	—5' 7".5
b	54.2	52.2	.484	7.1
c	56.2	54.2	.591	7.8
d	58.9	56.9	.524	7.3
e	61.0	59.0	.573	7.7
Mean	10 ^h 56 ^m .5	14 ^h 54 ^m .5	—5' 7".5 \pm 0".11	
			Corr. for Refraction	—0".2
			“ Parallax	+0".6

On the first plate (a), two images were measured and three on each of the others. Each plate was measured twice, so that the mean results rest on 28 complete measures.

The double star γ Virginis gave two parallel trails on each plate, and the differences given above, refer to the companion nearest the planet. The difference between the two companions was also measured, and was found to be the same, as given above, Table III.

The declination of Saturn and its comparison with the Ephemeris is obtained as follows:

Observed Differences:	—0°	5'	7''1	
Reduction to $\frac{1}{2}(\gamma^1 + \gamma^2)$:			—2.5	
Declination of γ Virginis:	—0	51'	56.3	(Berlin Jahrbuch.)
Declination of Saturn:	—0	57'	5''9	(1893, April 8, 14 ^h 54 ^m 5 Gr. M. T.)
American Ephemeris:	—0	57'	4''6	
Photogr.—Ephem.=			—1''3	

A similar correction to the British Nautical Almanac was found from visual observations at Greenwich and Windsor (Monthly Notices, vol. 51, pp. 374 and 500).

CHAPTER II.

OCCULTATIONS.

Occultations of stars by planets and the moon, or of the satellites of Jupiter, have not as yet been studied by this method, and it is not easy to form, in advance, any opinion as to its practicability. Theoretically, the photochronograph would record the time of the star's disappearance and reappearance to the nearest second. Regular work of this kind with the present equipment is out of the question, since the occultation of bright stars is so rare a phenomenon. Indeed, the ephemeris of occultations by planets for 1894, given in the A. N., No. 3198, pp. 97–102, contains only two stars above the sixth magnitude, and in both cases the occultation occurs here in full daylight.

CHAPTER III.

JUPITER'S SATELLITES.

A single night's experiments proved that the four *Satellites of Jupiter* could be photographed, in something less than half a second. The planet took just two minutes of time to pass over the photographic plate, and as ten seconds were allowed to elapse between each exposure, there were about a dozen pictures of planet and satellites on each plate. One of the exposures, on each plate, was made longer than the others (one or two seconds), in order to identify the dots representing the satellites belonging to each photographed disk of the planet, and to determine the direction of the diurnal motion ; so that one disk and its corresponding dots were drawn out into dashes. The fourth satellite was not measured, as it fell too far out of the range of our micrometer microscope.

Each exposure was made coincident with the beats of a chronometer, marking half seconds, and the time was recorded in the observation book. The measures of all the photographs on one plate were combined into a mean, as was also the corresponding times. One of the differences between these photographic measures and visual observations, is, that in the former, the values obtained for the angles and distances are *strictly simultaneous*, and the mean results from one plate represent these quantities, *for the short interval of two minutes of time*.

The results given below, depend on the measures of eight plates photographed under these conditions. As on each of these plates the same images have been measured for the three satellites, the data that remain the same are given first, and are referred to only by the plate number. The time given is the arithmetical mean of the times to which the images of the same plate belong, and n is the number of these images. These last are, as a rule, ten seconds of time apart, except where some had to be rejected as unfit for measurement. The progressive errors of the micrometer screw have been applied, but not the periodic, nor have the errors of the position circle been taken into account. Wherever the distances went beyond thirty revolutions of the micrometer screw, it was split in two by means of an intermediate speck. The distances and position angles of the satellites were referred directly to the planet's centre, and not to its limbs, as the outlines of the photographic disk are not as sharp as in the visual image.

TABLE VI.

DESCRIPTION OF THE PLATES.

Plate.	Date.	Sid. Time.	Greenw. Mean Time.	n
634	1893, Dec. 24	2 ^h 40 ^m 42 ^s 8	13 ^h 34 ^m 48 ^s 5	7
636	“	49 47.3	42 53.5	10
644	1893, Dec. 26	4 32 23.0	15 17 20.6	8
646	“	39 50.5	24 46.9	8
650	“	54 6.7	39 0.7	8
651	1894, Jan. 1	4 15 27.8	14 36 52.7	8
655	“	28 54.0	50 16.7	8
659	“	42 54.0	15 4 14.4	8

TABLE VII.

MEASURES AND REDUCTIONS OF ANGLE AND DISTANCE.

Satellite I.

Plate.	Pos. Angle.	Refr.	Phase.	Distance.		Refr.	Phase.
634	72° 3	0	0	16 ^R 49	108 ^{''} 9	0	—0 ^{''} 1
636	.3	0	0	.72	110.5	0	—0.1
644	76.3	0	0	19.03	125.7	0	—0.1
646	.3	0	0	18.95	125.2	0	—0.1
650	.3	0	0	18.54	122.5	0	—0.1
651	253.5	0	0	19.08	126.0	0	+0.1
655	.3	0	0	.34	127.8	0	+0.1
659	.2	0	0	.47	128.6	0	+0.1

Satellite II.

Plate.	Pos. Angle.	Refr.	Phase.	Distance.		Refr.	Phase.
634	76° 5	0	0	28 ^R 43	187''8	+0''1	—0''1
636	.4	0	0	.33	.2	+0.1	—0.1
644	260.2	0	0	16.44	108.6	0	+0.1
646	.2	0	0	.08	106.2	0	+0.1
650	.4	0	0	15.67	103.5	0	+0.1
651	249.5	0	0	19.12	126.3	0	+0.1
655	.3	0	0	.57	129.3	0	+0.1
659	.3	0	0	.88	131.3	0	+0.1

Satellite III.

Plate.	Pos. Angle.	Refr.	Phase.	Distance.		Refr.	Phase.
634	73° 1	0	0	47 ^R 85	316''1	+0''1	—0''1
636	.1	0	0	.94	.7	+0.1	—0.1
644	91.0	0	0	10.39	68.6	0	—0.1
646	.3	0	0	.27	67.8	0	—0.1
650	.6	0	0	9.74	64.3	0	—0.1
651	75.5	0	0	48.56	320.8	+0.1	—0.1
655	.5	0	0	.42	319.9	+0.1	—0.1
659	.8	0	0	.24	318.7	+0.1	—0.1

TABLE VIII.

FINAL RESULTS.

Plate.	Satellite I.		Satellite II.		Satellite III.	
634	p=72° 3	s=108'' 8	p=76° 5	s=187'' 8	p=73° 1	s=316'' 1
636	72.3	110.4	76.4	187.2	73.1	316.7
644	76.3	125.6	260.2	108.7	91.0	68.5
646	76.3	125.1	260.2	105.8	91.3	67.7
650	76.3	122.4	260.4	103.6	91.6	64.2
651	253.5	126.1	249.5	126.4	75.5	320.8
655	253.3	127.9	249.3	129.4	75.5	319.9
659	253.2	128.7	249.3	131.4	75.8	318.7

The times corresponding to these measures and results are given in Table VI, page 120. The reduction to the mean distance of the planet from the sun, and the correction for the equation of light have not been applied. There is no intention of utilizing these observations for the elements of the orbits, since the number is so small. The object in view, is to bring out clearly with what ease the satellites of Jupiter can be photographed, and the large number of photographs obtainable in a single night. There is no difficulty at all in exposing 25 plates an hour, which means 300 photographs in all. The real work falls on the observer at the microscope, but obviously, he has all the advantages of leisure, and the conveniences of position and temperature afforded by the computing room.

As has already been said, a great advantage of the photochronographic method, is the permanent record of the satellites' positions on the sensitive plates, which can be re-examined at any time, as long as the film can be considered trustworthy. No question as to instrumental constants can arise to trouble the computer, the only number not deduced from the plate, being the recorded time of the photographs. The value of one revolution of the micrometer screw can always be exactly determined for any microscope, or any special focal length, from fixed stars near the equator photographed in this fashion, the exposures being made automatically by the clock. The importance of this remark is conspicuously exemplified in the rediscussion of old observations of these satellites, to be mentioned below,

Perhaps, it may not be out of place to say a word or two in favor of the measures as given above. For this it will be enough to mention the very words of Bessel (*Astr. Unders.*, B. II, p. 11), who recommended observations of distance and position angle at all elongations, and to note the fact that these observations, as far as number is concerned, are far behind those of eclipses, occultations and transits. Mr. Marth, who by his invaluable computations of tables, is more than any other competent to judge of the requirements of the case, lays great stress on the importance of micrometrical measures of the two outer satellites (*Monthly Not.*, vol. 44, pp. 241-244).

The first complete series of distances for the four satellites, was made at the Vienna Observatory by Triesnecker, in the years 1794-1795 (*Wiener Ephemeriden*, f. 1797), a work highly praised by Bessel (*loc. cit.*, pp. 2-3). The observations were made with a Dolland objective micrometer, similar in principle to the heliometer, and they have been rediscussed and recomputed by Dr. Schur.

There are no recorded observations after these until 1832, when Airy, at Greenwich, began a series on satellite IV, which extended to 1836. He observed the differences of R. A. between the planet and the satellite, near the time of greatest elongation (*Mem. R. A. S.*, vol. 6, p. 83; vol. 8, p. 33; vol. 9, p. 7; vol. 10, p. 43).

About the same time (1835) the distances of this same satellite IV, were observed by Santini in Padua with an Amici double-image micrometer, situated between the objective and the eyepiece, and similar in principle to the heliometer (*Modena, Mem. della Soc. Ital. delle Sc.*, t. 21, p. 323).

Bessel's classic treatise on this subject appeared for the first time in 1842 (*Astr. Unders.*, Bd. II). His observations on the distances of the four satellites, and the position angles of III and IV, extend from 1832 to 1839, and were made with the Königsberg heliometer. They have been rediscussed by Dr. Schur.

After Bessel comes Jacob, in Madras, in the year 1857, who observed the position angles and distances of III and IV, with a 6.3 inch equatorial and filar micrometer (*Mem. R. A. S.*, vol. 28, p. 109).

Luther, 1856, made a few observations of the position angles and distances of the four satellites, with the Königsberg heliometer.

Vogel (*Astr. Nach.* Bd. 81, p. 113) observed the differences of R. A. between the planet and satellites III and IV, near the time of their greatest elongation.

The latest observations published are those by Dr. Schur, made in the years 1874, 1876, 1879 and 1880. (*Nova Acta der Ksl. Leop. Carol. Deutschen Akademie d. Naturf.* Bd. 45,

No. 3, Halle, 1882.) He measured the position angles and distances of the four satellites with a heliometer, and rediscussed previous observations.

Similar observations are now being made in several observatories, but the results have not yet been made known.

A series of photochronographic observations of the four satellites, at the time of opposition of the planet, for several nights in succession, could not fail to furnish valuable material for a new determination of their orbits and of the mass of the system.

CHAPTER IV.

SATURN'S RING AND JUPITER'S EQUATORIAL BELTS.

Saturn's ring and Jupiter's equatorial belts have also been made the subject of experiment with the photochronograph. These experiments were quite as instructive as any of the preceding inasmuch as they placed a limit to the photochronographic method. For the practical results go to show that for these and similar objects, where there is question of measuring *outlines* and investigating detail, the usual method of magnifying the object and following it in its diurnal motion with the driving-clock, seems to be preferable. This will appear from an inspection of the results. *Saturn's ring* was photographed with a half second exposure. The angle between the direction of the diurnal motion (indicated by the row of images), and the major axis of the apparent ellipse of the ring, was not difficult to measure.

TABLE IX.

INCLINATION OF SEMI-MAJOR AXIS OF SATURN'S RING TO PARALLEL,

1893, JAN. 12, 9^h LOCAL MEAN TIME.

Group.	1	2	3	4	5	6	Mean.
Plate 365	3° 46	3° 29	3° 18	2° 77	2° 97	3° 44	—3° 18
366	2.87	3.00	3.00	2.84	3.06	3.19	—2.99
367	3.06	2.96	3.08	3.01	3.18	2.89	—3.03
368	2.94	3.33	3.08	2.88	3.10	2.83	—3.02
370	3.03	3.09	3.02	3.04	3.38	3.01	—3.09
371	2.87	3.03	3.01	2.90	2.73	2.65	—2.86

$$p = -3^{\circ} 028 \pm 0^{\circ} 021.$$

The inclination is reckoned in the usual way, from east towards south.

Each plate contained six groups of images simultaneously visible in the microscope, with six or eight images of the planet in each group. The probable error of a single group, computed from the agreement among the groups, is $\pm 0^{\circ} 126$.

The probable error, $\pm 0^{\circ} 021 = \pm 1' 26$ of the resulting value is presumably as small as it can well be made by any single night's work in the visual method, yet the result differs from the computed value by half a degree, viz.:

$$p = -3^{\circ} 028 = -3^{\circ} 1' 7; \text{ Amer. Eph.: } p = -3^{\circ} 32' 0; \text{ B. J.: } p = -3^{\circ} 31' 8.$$

The source of the discrepancy lies in a constant error by which the method employed was affected.

Since the instrument was clamped, and the exposure lasted half a second, the resulting photographic image was built up of a series of overlapping images of the planet and its ring. Let AB denote the major axis of the ring at the beginning of the exposure, and A'B' at the end of it, then the line, actually measured, was presumably neither AB nor A'B', but the longer diagonal of the parallelogram AB B'A'. The measured angle p is therefore numerically *too small by the angle between this diagonal and the major axis*.

This angle can be computed from the major axis of the apparent ellipse of the ring $=40''.06$, and the motion of the planet during the exposure $0^{\circ} 5' = 7''.5$ (the declination of Saturn for that day being $-0^{\circ} 5'$), and is found to be $0^{\circ} 56' = 33' 6$. The angle p would consequently be:

$$p = -(3^{\circ} 1' 7 + 33' 6) = -3^{\circ} 35' 3,$$

which agrees fairly well with the computed angle.

This correction is still somewhat uncertain, as the $\frac{1}{2}$ second exposure was made by hand, and as the actinic action may not be quite instantaneous, or may spread on the plates; so that these measures are scarcely available for a computation of the angle between the ring plane and Saturn's orbit. For a comparison of these photographic measures with visual ones, the reader may consult Bessel's *Abhandlungen*, vol. I, pp. 110, 150 and 319, and *Monthly Notices R. A. S.*, vol. 42, pp. 304-308, with remarks by Oudemans, vol. 49, pp. 54, 55.

CHAPTER V.

EQUATORIAL BELTS OF JUPITER.

The *equatorial belts of Jupiter* were photographed with an exposure as short as it could be made by means of a switch. There were about 24 images on each plate, 5 seconds of time apart. *Only two large equatorial belts* could be perceived on the disks. On each plate, ten of the best images were selected, and each of the following numbers is the mean of ten or more measures. An exception was made with the last plate 649, which was difficult to measure, and on which 20 images were used. The time given is simply the middle time of the exposure of the plate, and it was not computed from the exposures of the measured images, as was done above, in the case of the satellites. The following two tables show the measures and the reductions :

TABLE X.
INCLINATION OF JUPITER'S BELTS TO THE PARALLEL,
1893, Dec. 26.

Plate.	Sid. Time.	Greenw. M. T.	N.	S.	Mean.
643	4 ^h 28 ^m .6	15 ^h 13 ^m .5	—14° 55	—14° 51	—14° 53
645	36.2	21.1	47	46	46
647	43.6	28.5	87	80	83
649	50.7	35.6	20	28	24
Mean :	15 ^h 24 ^m .7				—14° 51.5

The inclinations are reckoned in the usual way, from east towards south. The letters N and S denote the northern and southern belts. These angles do not require any correction for the diurnal motion of the image on the plate, since the central parts, and not the extremities of the bands were measured, quite otherwise than in the case of Saturn's ring.

TABLE XI.

DISTANCES OF JUPITER'S BELTS FROM NORTH POLE AND CENTRE.

Plate.	Distance from N. P.		Minor Axis.	Distance from Centre.		Relative Dist.
	N.	S.		N.	S.	
643	2 ^R 134	3 ^R 704	5 ^R 838	+0.269	—0.269	0.538
645	199	753	5.887	253	275	528
647	264	869	6.113	259	266	525
649	231	818	5.975	253	278	531

The distances in the second, third and fourth columns are expressed in revolutions of the micrometer screw, while for those of the fifth, sixth and seventh columns, the semi-minor axis was taken as unit.

The numbers headed : *Minor Axis* represent *the minor axis of the actual images on each plate* (the mean of ten images), *not the polar axis of the planet*, and this for several reasons. *First*, the action of the actinic rays *may go beyond or fall short* of the outlines of the optical images, by amounts which are not yet accessible to computation. *Next*, this action is a *function of the time of exposure*, and this, however short, *varied* from one image to another. *Finally*, the elliptical images on the plate represent *a series of overlapping images* of the planet, which tends to lengthen both axes, though the increase of the equatorial is greater than that of the polar, and, consequently, *the flattening of the planet would always come out too great* in this kind of photograph. For these reasons, the distances in the second, third and fourth columns of the preceding table have only a relative value for each plate, and, therefore, the distances of the belts in the last three columns, have been expressed in units of the semi-minor axis.

If it be desired to deduce the zenographical latitudes of the two belts, from these imperfect data, the following are the results :

TABLE XII.

ZENOGRAPHICAL LATITUDE OF EQUATORIAL BELTS, DEC. 26, 1893.

	Mean Distance from Centre.	True Latitude.
North Belt	+ 0.258	+ 17° 7
South Belt	— 0.272	— 11° 1

These latitudes have been computed by means of Freeman's formula, in the *Monthly Notices*, vol. 54, p. 29, with Marth's data, *ibid.*, vol. 53, pp. 458, 459. Comparison of these measures with those made directly from Prof. Holden's photographs of Jupiter (*Monthly Notices*, vol. 51, p. 402, compare vol. 52, p. 499, and vol. 53, p. 445) shows clearly that for surface detail and sharpness of outline, enlarged photographs are superior to primary images.

In conclusion, however, it may be fairly urged that whenever the centres of images are alone needed, as in the measurement of position angles and distances, a series of photochromographic primary images, offers very great advantages, since the centres of these images always represent the true place of the celestial object, for the middle of the time of exposure, however diffused the outlines may be.

GEORGETOWN COLLEGE OBSERVATORY.

SUGGESTIONS

REGARDING THE APPLICATION

OF THE

PHOTOCHRONOGRAPH.

STORMONT & JACKSON,
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1894.

PREFACE.

In the following paper, the last of this volume, some suggestions are offered regarding the applicability of the photochronograph.

In the first chapter the reader will find the description of a third form of photochronograph, which may be distinguished from the bar and disk photochronographs as the gridiron photochronograph. The difference between these three instruments is not essential, as it consists merely in the form of the shutter.

In connection with these various forms of the photochronograph we would call special attention to the second chapter, which resumes what has been briefly indicated in various places of this volume and in the Astr. Nachr. (No. 3058), regarding the general applicability of this instrument in celestial photography.

GEORGETOWN COLLEGE OBSERVATORY, *January* 6, 1894.

J. G. HAGEN, S. J.

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SUGGESTIONS

REGARDING THE APPLICATION

OF THE

PHOTOCHRONOGRAPH.

By JOHN T. HEDRICK, S. J.

CHAPTER I.

THE PHOTOCHRONOGRAPH IN PRIME VERTICAL AND ALTAZIMUTH TRANSITS.

1. *Introduction.*—The photochronograph was devised for the photographic observation of meridian transits, but it can also be adapted to prime vertical transits, or to transits in any vertical. The existence of personal equation is of little or no moment in prime vertical observations, if it is constant during the short time taken by the observation of each star, and even although it should not be the same for different stars, *e. g.*, for bright and faint stars, since the observations of each star give independent results. Variations in its value which seem more probable than with meridian observations, on account of the oblique motion of a star, can also be expected to disappear, as regards their effect, from a large number of observations, provided they are unsystematic. It seems, however, that there may exist a systematic difference in the personal equation for the east and west prime vertical, namely, when an observer has a different personal equation for opposite direction of motion of a star. In the two verticals the direction of motion is not merely opposite in the vertical direction, but the two paths form an angle with each other, except at the very zenith. For the east vertical the motion in the telescope is downwards and from right to left, or from the first to the third quadrant, and in the west vertical, upwards and from right to left, or from the fourth to the second quadrant.

2. Photochronograph Covering the Whole Field.—If it be desired to observe prime vertical transits by photography, whether to avoid personal equation, to obtain a permanent record, or to secure a greater number of observations, this can be done by a photochronograph which covers the whole field of view with alternate exposures and eclipses.

One form of this kind has already been described on pages 64 and 65, viz., the *occulting disk* with circular motion.

The form here suggested is a shutter, made of a light square, or rectangular, piece of metal, out of which are cut parallel openings of equal width with the strips of metal left between them. This shutter is placed near the focal plane, and is moved backwards and forwards across the field of view, perpendicularly to both the optical axis and the length of the openings, by means of an electro-magnet and a current, made intermittent by a clock.

The shutter may move either in grooves or on bars attached to the inside of the draw tube, but if there is fear that the motion will jar the draw tube, the bars can be extended through small holes in the draw tube and attached to a support which is connected with the main body of the telescope.

The width of both openings and strips should be equal to the amount of motion given to the shutter by the electro-magnet. If the armature of the magnet is attached directly to the shutter, the width cannot be greater than the greatest distance at which the armature is acted on by the magnet with sufficient promptness, when the current is remade. If, however, one desires to have a greater width to the openings and strips, the armature may be connected with the shutter by a lever, and its motion thus magnified. The first arrangement is preferable, as simpler, and avoiding all lost motion.

The electric signals sent by the clock to the magnet should be alternate makes and breaks of the same length. With the ordinary clock these signals would each be one second long, and this would be the length of the successive exposures. If this exposure time is too great for some of the stars, wire screens may be held before the object glass, and their brightness sufficiently diminished. If too great for all the stars observed one might also make use of a clock whose pendulum has a shorter time of swing, a half second, for example.

With the clock sending such signals, it is easy to see how the shutter acts. With the shutter in one position, *e. g.*, with the circuit open, the images formed in the openings of the shutter will be impressed on the sensitive plate. When the circuit is closed, the shutter is drawn to one side, each opening is replaced by one of the intervening strips, and each strip by one of the openings. The parts of the sensitive plate which were exposed before are now covered up and the parts before covered are now exposed, to be impressed by the images formed on them.

With the succeeding break of the circuit the same parts of the plate are exposed and covered, as at the beginning. Thus with the alternating motion of the shutter the whole plate is alternately exposed and covered, and the trail which would be made on the plate by a star moving anywhere across the field of view is broken up into short dashes separated by equal intervals. A suitable omission of clock signals at certain seconds will enable one to identify the second during which each dash was impressed on the plate.

For prime vertical transits the direction of motion of the vibrating shutter should be horizontal as the motion of the stars near the prime vertical is nearly up and down. As this motion is not, however, exactly up and down, it may sometimes happen that the star image passes from an opening of the shutter onto a strip during the interval between make and break of the circuit, thus causing an irregularity in the recorded impressions on the plate. Again, as the shutter can not be placed very close to the sensitive plate, it may fail to cut off or let pass all the light from a star, when the image falls near the edge of an opening. But in either of these cases inspection or measurement of the plate will practically clear up any doubts, except in some rare instances, where one or two of the star images on the plate may be lost to measurement.

The shutter may be moved by a single electro-magnet with a spring acting against it, or, as this arrangement is not symmetrical with regard to the collimation axis, there may be two magnets, one on either side of the telescope. The clock should then send the current through them alternately, instead of making and breaking it.

3. Use of the Double-bar Photochronograph.—In prime vertical observations quite a sufficient number of star images will probably be found within as much of the sensitive plate as is covered by a single strip of the shutter. If this is so, then the shutter can be reduced to two strips only, at equal distances from the centre of the field. When the instrument is reversed on each vertical, only one of these strips would be in use for one complete transit, as the reversal of the instrument would transfer it from the preceding to the following side of the prime vertical. The second strip is necessary in order to be able to begin an observation in either position of the instrument, clamp north or clamp south.

For the shutter thus reduced to two strips with the intervening opening, there may be substituted the double-bar photochronograph, illustrated on Plate IV. and described on page 45. Or the two strips may be separated from each other and each moved independently by an electro-magnet on its own side, making what is merely a different mechanical arrangement of the double-bar photochronograph. In either arrangement the two independent bars can be brought as near to the centre of the field as one may wish, while with the single shutter, the two

strips must be their own width apart. Again, if the two independent bars have a play greater than is necessary, it will do no harm, while the space through which the single shutter is vibrated by the magnet must be so adjusted as to be closely equal to the width of the opening.

But both the single shutter and the two independent bars allow the same variation in the length of either exposure or eclipse, that is possible with the original photochronograph. Thus, for example, the exposure may be $\frac{1}{10}$ sec. and the eclipse $\frac{9}{10}$ sec., or the former may be 1 sec. and the latter 4 sec., etc.

4. Wires in the Field of View.—It is necessary for the measurement of the photographic plates that there should be one, or several vertical wires in the focus of the telescope. These are to be impressed on the plates by the method used in meridian transits, namely, by throwing light down the telescope through the object glass and thus slightly fogging the plates except where they are covered by the wires.

When the plates are mounted in the microscope for measurement the wire images impressed on them will give their orientation, or, will enable one to measure the star images in a direction perpendicular to the prime vertical. The wires also enable one to use different sensitive plates for the two verticals, which it may be necessary to do in order to take one or both of the transits of a second star between the two transits of the first. Since the wires indicate the same points of the field, by measuring them along with the star images, the latter are referred to the same points of the field, although on different plates. It is evidently better to leave the plate undisturbed during both transits of a star. When this is done, the wires are needed for orientation only, though a measurement of their distance may serve as a control over distortion of the sensitive film.

With the whole field shutter, the wires should be placed so that they will all come opposite openings in one position of the shutter. Half the field will be slightly fogged, but this does not seem to cause any serious practical inconvenience.

With the two strip shutter or the double bars, the part of the plate in which lie the star images to be measured is covered up when photographing the wires, and hence is free from fog. With either of them, three wires would be sufficient, one in the middle of the field and one on either side of the strips or bars. In order to photograph the first of these wires the double bars should not overlap in the middle of the field, as they do in the zenith telescope. No star images will be lost by this, as the reversal of the instrument takes place during this part of the transit.

5. Reversal of the Instrument.—Any system of reversing the instrument used for visual observations can be followed with this method of applying photography, and with the same

elimination of the instrumental constants. When the instrument is reversed on each vertical the two trails from the two sides of one vertical will be on the same part of the plate and will be roughly parallel. Hence, the two settings in zenith distance should be such that the two trails do not obscure each other. The trails from the two sides of the other vertical will make an angle with the former, and will hence be usually readily distinguishable.

6. Reduction of the Observations.—The measures of the separate star images can be reduced to any of the wires of the field, or, if the plate is not disturbed between the two verticals, to any arbitrary point, *i. e.*, arbitrary micrometer reading, if one desires to do this. Or the method of reduction may be followed, which was used by Struve (*Astr. Nach.* XX, 217), for observations of γ Ursae Majoris, a star which approached but did not cross the prime vertical, and for which the micrometer wire was employed instead of the fixed wires, in order to increase the number of transits. This method is also given by Chauvenet, Vol. II, page 278.

7. Quickness of the Photographic Method.—The observation on either vertical will take less time than in the visual method, as the image photographed at each alternation of the shutter seems equivalent to a single wire. Since it is not necessary to follow the star in zenith distance, the level can be read during the actual observation. Since the observer has not to rise from the observing chair, the whole reversal of the instrument will take but a short time and observations can be secured nearer the prime vertical. More stars can, consequently, be taken in a given time by the photographic than by the visual method. The resulting advantage will depend, of course, on the number of suitable stars.

8. Screw Value of the Measuring Microscope.—As in any use of the photochronograph, the value of one revolution of the measuring screw can be derived from plates taken in the regular course of observation. (See the following chapter.)

9. Application to the Altazimuth. Transits over Horizontal Wires.—The photochronograph described in No. 2, and covering the whole field of view, is applicable to the altazimuth instrument or to transits in any vertical. The best fixed position for it would be with the slits of the shutter vertical and the motion horizontal.

If the field contains horizontal wires also, the parts of these which are impressed on the plate through the openings will be sufficient to give their positions exactly, and hence the times of transit over them may be derived from the plates as well as the times of transit over the vertical wires.

CHAPTER II.

THE DETERMINATION OF SCALE VALUES ON PHOTOGRAPHIC PLATES.

The purpose of the present chapter is to call attention to the use of the *photochronograph* as a general instrument for determining, in any application of photography to celestial objects, the angular values of distances on the plates taken, and consequently the angular value of the scale or screw used for measuring them, and to the *fundamental* or independent character of these determinations.

1. There are *three independent bases* for angular values : 1st, the *diurnal motion*, interpolated by a clock ; 2d, *graduated circles* ; and 3d, *divided scales*.

The use of the first basis requires a knowledge of the rate of the clock, which, in practice, is generally derived from previous determinations of right ascension. But as the effect of the clock rate, or of errors in its value, can readily be made evanescent for short intervals, the diurnal motion is practically an independent basis as far as angular values for photographic plates are concerned.

The use of the second basis, applied directly to a plate, can not furnish complete measures, but only a single co-ordinate, the position angle.

The third basis was used by Bessel in his method of measuring the focal length of a telescope. (Abh. Bd. II, p. 107.) But it does not seem to be practicably applicable to photographic telescopes, except where the visual and the photographic foci are sensibly coincident, since the determination of the photographic focus is rather a tedious operation.

2. In practice, the measurement of photographic plates has generally been founded on differences of right ascension and declination furnished by *other instruments*. Without raising any objection whatever against this method, it seems certainly preferable to make the determination of the scale value of a plate an independent one.

3. The following methods of independent determination from the diurnal motion have sometimes been used. A star was allowed to trail across the plate and breaks were made in the trail at known moments. Or the star was allowed to trail for a known length of time. Or, finally, a short exposure was given at one moment and after the lapse of a known interval another short exposure was given.

If the exposure of a star and the interruption of its light, which are used in these methods, were made automatically by a clock, there would be no objection to the first and third on the score of accuracy, provided that the distance of the points from which the scale-value is deduced is not less, or not much less, than the greatest distance to be measured on the plate. Moreover, there should be a group of points and not a single point at each extremity of the standard distance. If, however, the exposure and interruption are made by hand, the accuracy of the determination will necessarily be less. In the second method there will be the uncertainty as to how long after the exposure it is before the action on the plate begins, the impossibility of setting a micrometer wire on the exact beginning of a star trail and the existence of only a single point of reference at either end of the trail.

4. The *photochronograph* is simply an instrument to produce exposure and eclipse in the field of a telescope by automatic signals from a clock. The continuous trail which would be traced by a star moving across the field of a stationary telescope is broken up by its use into a series of dots or dashes, whose centres correspond to moments of time, which are accurately known. These dots or dashes constitute a *time scale*, impressed on the plate, in time of the parallel of declination, and from them the scale value in arc is readily computed. The determination of the scale is consequently an *independent* one, based on the diurnal motion.

The form of the *shutter* used in the photochronograph is merely a detail. Particular circumstances may readily suggest other forms than those described in the foregoing pages, viz.: the bar, page 11 and Plate I.; the disk, page 64 and Plate IV., and the gridiron, page 136.

5. The *usefulness* of such a scale for the measurement of photographic plates is sufficiently obvious, but some of its features may be given more specifically.

The time scale can be made as long as the breadth of the plate in the parallel of declination will allow. In a square plate it may be made twice as long as the greatest rectangular co-ordinate from the centre of the plate, or between $\frac{2}{3}$ and $\frac{3}{4}$ as long as the greatest distance that can be measured on the plate. It is evident that positions resulting from the measures of the plate will be here more accurate than if the scale value is deduced from a less distance.

The accuracy with which the distance between the extremities of the time scale is known is probably greater than for two points of the field, whose distance is concluded from ordinary meridian observations, for the distance depends for its accuracy on the rate of the clock only; and it is given directly by the clock instead of being the difference of two independent star positions, and hence less accurate than either of these positions. Moreover with the time scale, the distance can be measured more accurately since the accidental error of single points may be somewhat eliminated by taking the mean of a group of points at either extremity.

In many applications of photography the time scale may be impressed on the plates exposed in the regular line of work and even during the regular exposure, as has been done here for our transit and double star observations and usually for our zenith telescope observations. When this is the case, a record of the scale value is preserved with each plate, *with but little, if any, additional labor*. And as this record is made concurrently and continuously with the plates themselves, there is no need of making more or less probable hypotheses as to the constancy or change of the scale value, such as are necessary when the scale value is determined at considerable intervals. The impressed time scale is also a check on distortion of the film during development.

But, when necessary, special plates may be exposed for the scale value. This requires, of course, some additional labor and time. The amount of the latter need not usually be much greater than the length in equatorial time of the time scale required. (See the following number.)

If there should be any reason to fear a change of focal length in the telescope during a long exposure, time scales may be taken before and after the regular exposure.

The time scale given by the photochronograph lies in the parallel of declination. The scale value of the plate in the hour circle is consequently given by inference, but by an inference that is commonly considered valid in other methods. With our zenith telescope time scales have sometimes been impressed on a plate nearly parallel to its meridian line, by placing the instrument near the prime vertical without disturbing the plate. By changing the position of a plate, time scales can, of course, be impressed on it in any direction.

A plate with a number of time scales between its northern and southern edges may be mentioned as possibly of use in centring the object-glass, or for studying the optical distortion of the field.

6. In choosing the *stars* which are used to impress the scale on a plate, only those stars can be taken whose brightness is sufficient to make a developable impression on the plate during the time of exposure given by the photochronograph. The following data may here be of value. The magnitudes given are photographic, or the average only of the visual magnitudes.

In our equatorial, whose aperture is 12 inches and focal length 15 feet, a star of the fifth magnitude, and on the equator, will give such an impression safely with an exposure of 1 second. In our zenith telescope, where the aperture is 6 inches and the focal length 35 inches, the magnitude 6.5 is sufficient with the same exposure, and the fifth magnitude with an exposure of one tenth of a second. A very good night will add half a magnitude to these numbers, or even a whole magnitude. The effect on the plate depends, of course, on the length of time that the star acts on a point of the plate, and hence on the declination of the star. By using stars towards the

poles and increasing the exposure time, still higher magnitudes may be used, though with an increase of the time needed for the same length of scale.

In visual observations slow moving stars are used for determining micrometer values, on account of the greater accuracy of the observation of a transit of such stars. But with the photochronograph the accuracy is the same in all parts of the sky. Hence, suitable stars can be found at almost any time, even when the observations are confined to one plane. With an equatorial the only delay will be the time required to set on the star chosen.

7. It seems needless to suggest in detail the different *kinds of photographic observations* in which the photochronograph may be used to give the scale value. We have employed it here in our observations with the transit instrument, the zenith telescope and the equatorial. One suggestion, however, it may be in place to make, namely, its application to the photographic plates that are being taken for the purpose of *charting the whole sky*.

By its use the measures of the relative positions of the stars of each plate could be made independent, the zero stars serving to fix the position of the centre of the plate. A smaller number of zero stars would then be needed than if the scale value also had to be deduced from them.

Except when the zero stars are numerous and in favorable positions, the error of the scale value, determined from their known co-ordinates, will be magnified in the deduced positions of some of the stars on the plate. With the time scale from the photochronograph, this will not be so. (See No. 5, beginning.) In some of the fields in the proposed distribution of the plates over the sky, it has been found that the number of sufficiently well determined stars is small.

If a plate somewhat larger than necessary is used, four time scales could be impressed on it at the four edges of that part which is to be measured. This would serve as some additional check on distortion of the film.

If the plate is not disturbed between the regular exposure and the impression of any one of these scales, the line of images will give the *orientation* of the plate.

CHAPTER III.

THE PHOTOCRONOGRAPH IN VISUAL OBSERVATIONS.

1. *Historical Notes.*—In addition to the various forms of apparatus which have been devised for the purpose of determining the absolute personal equation in the ordinary methods of observation of transits, there have also been suggested apparatus and methods of observation with the end of annulling, or at least reducing, the equation itself. The general principle of these is to cause the wire (or wires) and the star to be relatively at rest.

This can be done in two ways. In the first, *the wire is moved* across the field of view at the same rate as the star, both of them being always in view. In the second, the wires are fixed and the wires and the star are *seen together only instantaneously*, or, at least, for such short times that the motion of the star during them is insensible. This, also, may be effected in two ways, namely, by giving an instantaneous view either of the wires or of the star. The mechanism used for the latter will commonly give the former also for those portions of the wires which are employed in the observation. These instantaneous views are regulated automatically by clock work.

There are thus three methods for eliminating or reducing the personal equation. In all three, there are experiments and trials by various observers, which are briefly mentioned below. The method which is suggested in this paper belongs to the third case.

(a.) In the earliest forms of the first method the wire was moved across the field of view by clock work. The bisection of the relatively stationary star was then made by an independent slow motion. Two forms of this kind were devised about the same time—in 1863—by A. Rédier, of Paris, and C. Braun, S. J. Descriptions of these can be found in an article by R. Radau ^(1.) Rédier's apparatus was tried in the Paris Observatory ^(2.) Father Braun's has never been tried, though complete drawings were made for it. In a publication of the Kalocsa Observatory ^(3.), he describes and illustrates it, and gives some improvements.

In a late form by J. Repsold ^(4.), the motion of the wire is produced by the hand of the

(1.) *Moniteur Scientifique* (Quesneville), Tome VII (de la collection), p. 1028, Paris, 1865. Also translated in *Repertorium für Physikalische Technik* von Dr. Ph. Carl, Band I, p. 311. München, 1866. *Les Mondes*, par M. l'abbé Moigno, Tome I, p. 491, Paris, 1863.

(2.) *Monthly Notices*, Vol. XXIV, p. 159, 1864. *The (London) Reader*, July 30, 1864, Vol. IV, p. 141.

(3.) *Berichte von dem Erzbischöfliche-Haynaldschen Observatorium zu Kalocsa in Ungarn*, von Carl Braun, S. J. Münster i. W., 1886.

(4.) *Astronomische Nachrichten*, Band 123, p. 177. 1889.

observer. The wire is set on the star and then made to follow it across the field by turning the two heads of a micrometer screw with the two hands. At *fixed points electrical signals are made automatically*, and registered on a chronograph. There is an account by Prof. Becker of some trials with this apparatus, in the *Astronomische Nachrichten* ⁽¹⁾.

(b.) In the method devised by S. P. Langley ⁽²⁾, then of the Allegheny Observatory, the relative change of position between the star and the wires is destroyed by making the latter visible momentarily. The wires, which are fixed, are arranged in groups, and within the groups the wires are one equatorial second apart. By a separate clock work the field is lit up by flashes of light at intervals equal to the time the star takes to pass over one equatorial second, and the wires are thus brought into view. The observer, without disturbing the running of this clock work, changes the time of occurrence of the flashes until they coincide with the bisection of the star by a wire. The coincidence will then occur at the remaining wires of the group. The moment of each flash is registered on a chronograph, and these registered moments are those of the transits over the wires after the coincidence is once established, which can be secured by the time that the second or third wire of the group is passed.

(c.) Finally, the relative motion may be destroyed by keeping the star usually hidden and exposing it momentarily at each beat of the clock. In 1865 C. Wolf, of the Paris Observatory, made some experiments ⁽³⁾ in which this was done with the artificial star of his apparatus for determining the absolute personal equation. In other respects, the usual method of observing by eye and ear with single wires was followed.

In 1889 a few trials were made at Greenwich on real stars. A shutter which covered the field of view was moved so as to uncover the wires and the star at each second. The account ⁽⁴⁾ is very short, but the usual eye and ear method was probably followed in other respects. The trials were not very successful on account of a defect in the apparatus.

Some further experiments ⁽⁵⁾ on artificial stars and planets were made in 1892 by Ch. André, director of the Lyons Observatory, and F. Gonnessiat, assistant, with the personal equation apparatus of the latter. The authors find that although the personal equation became very small, it was not entirely eliminated.

(d.) The method proposed here is that of the experiments mentioned in (c), except in the wire system employed. The apparatus for giving the successive exposures of the star and

(1.) A. N., No. 3036, Band 127, p. 185. 1891.

(2.) American Journal of Science. Vol. 14, p. 55. July, 1877.

(3.) Annales de l'Observatoire Impérial de Paris, Mémoires, Tome. VIII, p. 194. Paris, 1866.

(4.) Observatory, Vol. XII, p. 391. Oct., 1889.

(5.) Comptes Rendus, Tome CXIV, pp. 157 and 893. 1892.

wires is the instrument called here the *photochronograph*, which was devised for the purpose of gaining the same end with a photographic plate instead of with the eye. It is illustrated on Plate I. and described on page 11. As the shutter is a narrow bar, only a small part of the field is covered up instead of the whole field as in the Greenwich experiments.

(e.) The *wire system* of the proposed method, and the method of referring the star to the wires, were derived from some experiments of Gonnessiat's with his personal equation apparatus, which are described in a paper on the personal equation, published first as a "Thèse soutenue devant la Faculté des Sciences de Paris," and afterwards enlarged and published by the Lyons Observatory ⁽¹⁾. In these experiments the usual method of observing with a single wire was not followed, but the position of the star at the moment of a signal from the clock was estimated *with respect to two wires between which the star was at that moment*. The signals from the clock were addressed to the ear in one experiment and to the eye in another, and were not a succession of signals in rhythm, but single signals. In the first case the equation was much reduced, and in the other it nearly vanished. Gonnessiat attributes the effect to the signals not being rhythmical, but it may be attributable, in part at least, to the use of the two wires, as has been already remarked by F. Tisserand in a review of the first form of the paper ⁽²⁾. In these experiments the artificial star appeared continuously during the transit.

This method of referring the position of the star to two wires offers, at any rate, the advantage of increased accuracy. In the proposed method the number of wires is increased, and, moreover, the star is seen in momentary positions only instead of being continually in view. That form of the method is described first which can be presented with the greatest clearness.

2. The Method of Observation.—The reticle consists of a sufficient number, say 5 or 7, of groups of wires. Each group contains *three wires*, as accurately as possible one equatorial second apart. The photochronograph (see Plate I.) is mounted at the side of the draw tube, its narrow shutter reaching across the central part of the field, as near the reticle as convenient on the objective side. The sidereal clock at each second breaks the circuit through its electro-magnet for a small fraction of a second, and during this time the shutter rises, is stationary and falls. The transit is set on a star and the latter brought by the slow motion under the vibrating shutter (and between the horizontal wires), so that at each vibration of the shutter it is exposed to view for a very short time. *While the star is passing through a group of wires the observer estimates its relative position with regard to the first and second wires, and then with regard to*

(1.) Travaux de l'Observatoire de Lyon, II. Recherches sur l'Equation Personelle par M. F. Gonnessiat, pages 131 and 134. Lyon, 1892. This paper is frequently referred to in the following pages.

(2.) Bulletin Astronomique, Tome IX, p. 251. June, 1892.

the second and third at the exposures which fall nearest to the middle wire, if there should be more than one exposure in either interval ⁽¹⁾. He then notes his estimates in the observing book, together with the number of the second for either or both of the exposures. In making the estimates of the relative positions, it will be better to estimate in both cases the distance from the middle wire towards the outer wire of the group.

The form of the record will be like the following fictitious example, where it is supposed that $\delta = 43^\circ 1$ (sec $\delta = 1.37$, cos $\delta = 0.73$) and that the middle wires of the groups are 15 seconds apart. The estimates for the different groups are here printed alongside of each other instead of under each other, as they would be written in the observing book.

I		II		III		IV		V		
9	.1	29	.5	50	.1	10	.6	31	.2	(1)
10	.7	30	.2	51	.6	11	.2	32	.5	

When the star was exposed at 9 seconds it was estimated to be distant from the second, or middle, wire by 1 tenth of the interval between the second and first wires. When exposed at 10 seconds it was distant from the second wire by 7 tenths of the interval between the second and third wires. At 29 seconds it was midway between the second and first wires of group II, &c.

If it should be necessary in order to avoid confusion while making the estimates, the count of the seconds may be dropped with the first estimate and taken again from the clock face before the next group. Or the second corresponding to the second estimate may be found by counting on from that estimate, looking at the clock face, and subtracting the number counted from the first second that is recognized from its face. But counting seconds becomes so mechanical with an observer that it would seem that it could be carried on through the estimates as easily as in the usual eye and ear observations. If, however, only one second is noted in the observing book, the other should be filled in before going on with the computations.

3. The Time of Transit over the Mean Wire.—Besides having the position of the star at the clock beat selected by the vibrating shutter, the observer make his estimates on what is actually before his eye, and does not have to compare his *recollections* of what has been seen.

(1.) For equatorial stars only two estimates can be made in each group. The number of estimates made is here restricted to two for all stars for the sake of uniformity and of simplicity alone. See No. 4, l. 6, from end. The restriction of the estimates to the two exposures nearest the middle wire is principally to fix one's ideas (see No. 5, par. 1), as is also the limitation of the number of wires. See No. 12.

Otherwise, this method and the usual one are closely alike in their general character and as far as the labor at the telescope is concerned, for example, in the number of estimates required. But the proposed method requires more computation to deduce the time of transit, as the tenths, estimated in equatorial time, have to be converted into time of the parallel of declination. We shall first consider the case of full observations.

(a.) It is obvious that one method of deducing the time of transit over the *middle* wire of each group is by doing with the recorded numbers by computation what the observer does by eye estimate in eye and ear observations; that is, by finding what part the distance from the middle wire at the first estimate is of the total distance between the two estimates.

From the example given before, we have:

$$\begin{array}{ccccc}
 \text{I} & \text{II} & \text{III} & \text{IV} & \text{V} \\
 9 + \frac{1}{1+7} & 29 + \frac{5}{5+2} & 50 + \frac{1}{1+6} & 10 + \frac{6}{6+2} & 31 + \frac{2}{2+5} \\
 9^{\text{s}} 12 & 29^{\text{s}} 71 & 50^{\text{s}} 14 & 10^{\text{s}} 75 & 31^{\text{s}} 29
 \end{array} \quad (2)$$

The computation itself is so simple that it will not take a great deal of time to write down the transits in a column left for the purpose in the observing book. The mean is then taken as usual.

(b.) The time of transit over the *mean* wire may also be found directly from the recorded numbers by adding to the mean of the round seconds of the first estimates the quotient of the sum of the tenths of the first estimates by the sum of the tenths of all the estimates. By first estimates are meant those made before the middle wires of the groups, those after them are called here the second estimates. We have from (1):

$$\begin{array}{rcl}
 \text{Mean of round seconds, } 49^{\text{s}} 80, & \text{Sum of first tenths, } 1.5, & \\
 1.5 \div 3.7 & 0.41, & \text{Sum of all tenths, } 3.7, \\
 \hline
 \text{Mean wire, } 50^{\text{s}} 21. & & (3)
 \end{array}$$

The use of this method of computation is equivalent to the use of a mean denominator in the fractions of (2) instead of the denominators from observation.

The same values will be found as in (2) and (3) if we substitute in the operations of (a) and (b), *second* estimate for *first* estimate, and *subtraction* of the quotient for *addition*.

(c.) If the estimates were both accurate and precise, the sum of the tenths of all the estimates would be $n \cos \delta$, where n is the number of groups. If, then, for the sum (*i. e.* the denominator in (b.)) we substitute this quantity, we shall secure slightly greater accuracy in the mean, which will be the same as the mean when all the estimates are reduced separately to the mean wire. But this greater accuracy is probably only apparent if we consider the probable error of any of the estimates.

The mean obtained from the first estimates (see (b), l. 4) alone will differ from that from the second alone when this substitution is made. The following precept will give the mean from all.

Call the tenths of the first estimates positive, and those of the second estimates negative. Divide the algebraic sum of all the tenths by $2n \cos \delta$. Add the quotient algebraically to the mean of all the round seconds, or, multiply the algebraic mean of the tenths by $\sec \delta$ and add the product to the mean of the round seconds.

In the example given $2n = 10$, and $\sec \delta = 1.37$, we have

Sum tenths first estimates,	+1.5	Mean of all seconds, 50 ^s 30
“ second “ ,	—2.2	—0.07 \times 1.37, —0.10
	-----	-----
Mean of estimates,	—0.07	Mean wire, 50 ^s 20

The multiplication by $\sec \delta$ can be readily performed by the slide rule or by the table for collimation error of transits. The slide rule could be graduated so that the argument would be the sum of the tenths instead of their mean.

4. Reduction of Separate Estimates to the Mean Wire.—To deduce from each estimate the time of transit over the mean wire, the equatorial interval from each estimated position to the mean wire must be multiplied by $\sec \delta$ and the product added to the corresponding second. As the estimated tenths are in equatorial time, the equatorial interval from each position to the mean wire is found by adding algebraically each estimated tenth to the equatorial interval for the middle wire of the group. As before, the tenths estimated after the middle wires of the groups are to be taken as negative. In practice, the addition of the tenths to the equatorial intervals of the middle wires can be done mentally.

The equatorial intervals of the middle wires being supposed, in the example given, to be $\pm 30^s 0$, $\pm 15^s 0$ and $0^s 0$, the intervals for the estimated positions will be :

I.	II.	III.	IV.	V.
+ 30 ^s 1,	+ 15 ^s 5,	+ 0 ^s 1,	-- 14 ^s 4,	-- 29 ^s 8,
+ 29.3,	+ 14.8,	-- 0.6,	-- 15.2,	-- 30.5.

Multiplying these by 1.37 ($= \sec \delta$) and adding the products to the corresponding seconds, we have :

I.	II.	III.	IV.	V.
50.24	50.23	50.14	50.27	50.17
50.14	50.28	50.18	50.18	50.22

Except for equatorial stars, more than two estimates of position can often be made within each group of wires. When this is done the time of transit over the mean wire can be computed from each estimate in the same way.

Instead of reducing to the mean of all wires, a reduction may be made in each group to the middle wire of the group by multiplying the estimated tenths by $\sec \delta$ and adding the product algebraically to the corresponding second.

5. Incomplete Observations.—In what precedes it has been supposed that the observation was complete, or that the two estimates required had been made in each group of wires. It was also said in No. 2 that the estimates were to be made at those two exposures of the star by the shutter which occur nearest to the middle wire on either side of it. It is evident that all that is essential is that two estimates of the position of the star should be made, one before and one after the middle wire. The observations within a group may consequently be completed when the estimate at the second exposure is missed, if another exposure occurs before the star leaves the group.

In an incomplete observation either, 1st, one or more entire groups are missing ; or, 2d, one of the necessary estimates is lost in one or more of the groups. When the first case is not combined with the second, any of the methods of No. 3 may be used and the transit over the mean wire found with the help of the equatorial intervals of the middle wires, exactly as in the ordinary method of observing. In the second case, whether combined with the first or not, the

simplest method of finding the time of transit is by reducing each estimate to the mean wire, which a computer is apt to prefer to do even in the ordinary observations.

6. Inaccuracy in the Wire Intervals.—It has also been supposed that the wires of each group are sensibly one equatorial second apart. The accuracy of these intervals depends on the accuracy with which the focal distance is determined and the accuracy with which the wires can be put in.

There is no reason why there should be any sensible error for the first cause in so short an interval as one second, if the precaution is taken of determining the value in seconds of a long distance on the reticle plate with the telescope adjusted to stellar focus before the ruling is done for the reticle.

But there will possibly be sensible inaccuracies in the reticle itself. In the Harvard Annals, ^(1.) Wm. A. Rogers instances a reticle ruled on glass in which the greatest error was 0^s.006. With the focal length of the telescope this is $1\frac{1}{4}\mu$. In a letter he says that “there should be no difficulty in ruling a glass reticle in which the error of spacing would not amount to more than 1μ at any point. By taking great care in the ruling it should not be difficult to reduce this limit to $\frac{1}{2}\mu$.” For a focal length of 137.5 cm. or 4 ft. 6 in., 1μ is equal to 0^s.01. Taking the upper limit, some of the wire intervals may consequently be out by as much as 0^s.02 in such a telescope. In another volume Prof. Rogers says that he could find no sensible loss of light with microscope cover glass ^(2.)

For a reticle of spider lines it should be possible to make the scores in the reticle plate which receive the wires with nearly the accuracy of the lines ruled on glass. Our best instrument makers can, probably, put in the spider lines as accurately as the scoring is done, or if the scores are a little wide, with greater accuracy by repeated trials, using a high magnifying power.

Inaccuracies of the amount given by Rogers will have practically no effect on the time of transit. If e' be the excess over 1 equatorial second of the first interval of a group, and e'' be that of the second interval, the correction needed for the transit over the mean wire computed from the two estimates made in the group will be $\frac{1}{2}(0.a(e' + e'')\sec\delta - e'')$ in time of the parallel, where a is the number of tenths in the first estimate. As the greatest value that $0.a$ can have is $\cos\delta$, the correction will lie between $+\frac{1}{2}e'$ and $-\frac{1}{2}e''$. Hence if the greatest error in any interval be 0^s.02 and this error be neglected in deducing the mean transit from the estimates

(1.) Annals of the Astronomical Observatory of Harvard College, Vol. XVI, p. xxiii.

(2.) Vol. X, p. xiii.

of the group, the *greatest error of the mean transit will be $\pm 0^s.01$ in time of the parallel*. Except in very rare cases, with $\pm 0^s.01$ for the maximum error in any group, the error which is probable in the mean of all the groups may safely be left to equate itself out in a series of observations.

It may be, however, that one can not secure great accuracy in the group intervals or it may become necessary to take account of their want of accuracy for some reason, such as broken transits or the making of more than two estimates within a group. If so, the recorded numbers can easily be corrected mentally for the excess or defect of the interval, entailing, however, this much additional computation.

Want of accuracy in the intended intervals *between the groups* is not a source of error. It is more convenient to have the side groups symmetrical with the middle group, but it is better that the intervals between the groups should not be equal so as to avoid a recurrence of the same tenths in the estimates.

7. *Smaller Group Intervals.*—The intervals between the wires of a group were put in No. 2 at one equatorial second, in correspondence with the beat of the regular astronomical clock. Both the accuracy and the precision of the observer's estimates of tenths of the intervals would be greater if the intervals were smaller. But the gain may be offset by practical difficulties. Half an equatorial second would seem to be a suitable interval, since with the magnifying powers usually employed the estimations of tenths with the eye and ear are made as readily near $\delta = 60^\circ$ ($\cos \delta = 0.5$) as at the equator. Some experiments also by Gonnessiat ^(1.) seem to indicate that such an interval is about as small as can be fractioned with accuracy in transits.

If the wires are placed at half second intervals and the clock beat whole seconds, the star would not be exposed between every pair of wires. There would have then to be five wires so as to secure an estimate on either side of the middle wire for stars of small declination. With so many wires before the eye, there might be confusion as to the interval within which the exposure fell.

If the clock beat is made the same as the wire interval, there would not be the same reason for confusion, since the star would be exposed within all the intervals. But the quick succession of the exposures may keep the observer from making the estimates with sufficient deliberation.

8. *Duration of Exposure.*—The star should be exposed by the shutter at each clock beat for as short a time as will allow the observer to see distinctly the star and the wires and to

(1.) Op. cit., p. 99.

make a careful estimate. For the latter, the length of exposure is of less consequence on account of the persistence of vision ⁽¹⁾. Probably it will not be possible to obtain from a clock electric signals of definite length and less than about 0^s 05. A few experiments made here with an exposure of 0^s 10 make it seem that an exposure of 0^s 05 would not be too short for distinct vision, especially as the observer would have a fairly close idea as to where the star was to appear. The wires also would be permanently visible above and below the shutter if a constant illumination be employed. Illuminating the wires instead of the field would probably give a more distinct view of them, but would make a difference between day and night observations.

9. Comparison with the Eye and Ear Method.—Some comparison of the eye and ear method with that proposed here was made in No. 3, but what was said there may be repeated. For brevity, the eye and ear method will be designated here by E-E, and the proposed, or instantaneous, method by I.

In E-E the observer has to select from a continuous path the position of the moving star at a given moment, and to do this has to co-ordinate the impressions on two different senses. In I the position of the star is selected by the shutter; the star, though really moving during the exposure, can hardly seem to the observer to do so; and but one sense is employed in the observation.

In E-E he has to compare the star and the wire actually before his eye with his recollection of the relative position of the star and wire at a preceding time, or rather he has to compare his recollections of the relative positions of star and wire at two or more different moments. The motion of the star before his eye tends to disturb his recollection of these positions. In I he has only to estimate what is actually before his eyes; and if the time of visibility, prolonged somewhat by the persistence of vision, is not felt to be sufficient for an exact estimate, and he founds his decision partly on memory, there has been no new impression to disturb or efface his recollection. (See No. 10, (c.)) The falling of the shutter may have some such effect, but to this one would probably get so accustomed as hardly to notice it.

In E-E the interval, the fraction of which has to be estimated, changes with the declination of the star; in I this interval is the same at all declinations.

In I all stars are observed in exactly the same way; while in E-E, and even in the chronographic method there is a difference in the way of observing when the star has a high declination.

In E-E the time required for an observation on all the threads increases with the declination and with very slow moving stars the observer is apt either to observe on fewer wires or

(1.) Vid. Gonnessiat, p. 147.

to make use of the movable wire. In I there will be necessarily some increase of the time with the declination, but with a certain declination the time can be diminished by making more estimates within a group, and thus obtaining *the same number of estimates with fewer groups*. The complete observation of very slow moving stars may be made even within the limits of the middle group of fixed wires. In I a micrometer may also be used, as in E-E. It should have, however, instead of a single wire, the same three wires as a fixed group, or, at least, two wires.

Moreover, since even one estimate of position while the star is within a group will give a time of transit, there will be somewhat less danger, in I, of losing a group entirely, *e. g.* in clouds, than there is of entirely losing a wire in E-E, where observation of the star must be secured near the single wire and on both sides of it.

Dr. Gonnessiat ^(1.) suggests that I would not prove applicable to faint stars. It is evident that the very faintest stars can not be observed, but only experience can show how far the loss extends and whether it causes any serious limitation of the powers of an instrument. The few experiments it has been possible to make here have left the impression that the loss will not be great and that any star that is easily followed in E-E can be fairly observed in I. There will be probably somewhat less difference between the two methods, if the wires are illuminated instead of the field.

The star image also is likely not to be as clear with the short exposure of I as when it is followed steadily.

With very bright stars where the image fills so large a part of the interval between the wires, the estimate of position in I will probably be less accurate, and especially, should the group interval be only about $0^{\circ} 5$. But observations of very bright stars are less accurate in all methods.

10. Personal Equation.—It is evident from the comparison of the two methods that the personal equation will be quite different in the proposed method from what it is in the eye and ear method. Experience alone will show with certainty what nature and amount the personal equation has, and to what variations it is subject. The latter point is really the one of much the greater importance. A machine too will have its equation, but with the difference that, after a sufficient investigation, the value of its equation in different circumstances can be predicted. The more like a machine an observer is, the more accurately can his observations be freed from errors depending on him.

(a.) The most obvious personal error to be expected in the proposed method is that arising from the observer's tenths of a wire interval not being of the same length, and probably

(1.) Op. cit. p. 162.

also from an unconscious attachment to certain numbers. This error is sometimes called the *decimal error*. The opinions of writers as to its constancy seem to be contradictory. There does not appear to be, however, any reason to expect abrupt changes in its amount, especially in a practised observer, although it may change somewhat in a period as long as a year. There is less reason for expecting fluctuations in its value in this method than with the eye and ear, since the interval to be divided is here always the same and is included between fixed points.

From the experiments mentioned at the end of No. 1, (c), page 145, André and Gonnessiat estimate their decimal errors at $-0^s.03$ and $-0^s.02$ respectively. The sign is reversed, of course, with the reversal of the direction of motion of the star.

An obvious way of studying directly the decimal error would be to have an assistant give various positions to an artificial star, and to then expose it for the observer's estimate for the same length of time as in the regular observations. Stars of different magnitudes may also be used. (See below, (b.)) It may be that by observations of this kind the observer may reduce his decimal error to insignificance.

Another method of directly investigating the decimal error would be to point the telescope on a slow moving star, and then either to call out the estimated tenths to a recorder at each exposure or to signal to a chronograph when the star is judged to pass from one tenth to the following one. A study of the record will show what are the relative lengths of the observer's tenths, and may possibly be sufficient to make some sort of separation between what is properly the decimal error and that due to his preference for certain numbers. A similar method is suggested by André in Gonnessiat's pamphlet ^(1.).

(b.) Another error of somewhat similar origin will be produced by a wrong estimate of the position of the centre of the star disk, and will cause a change of personal equation with the magnitude of the star. This will probably not be of quite the same amount with a moving star as with one practically stationary. When at the exposure the star is entirely free of the wires, it should be quite small, but it will be likely to have a different value when a wire lies over one or the other side of the disk. Hence, this error will be, in part, included in the decimal error, and may cause it to vary somewhat with the magnitude of the star.

Gonnessiat ^(2.) estimates the equation for the correction of this class of error in chronographic observations at from $-0^s.10$ to $+0^s.10$. But the circumstances are different with such observations, as the star is seen continuously.

(c.) The star really moves, however, during the exposure. On account of the persistence of vision, if the time of exposure is $0^s.05$, which seems to be a fair value for the time that the

(1.) Op. cit., p. 145.

(2.) Op. cit., p. 166.

impression on the retina persists, then at the moment the shutter falls the observer is actually seeing all the positions of its image during the time of exposure. If the estimate of position with regard to the wires were made at the moment of the shutter's fall, the observer would estimate correctly, since the centre of the image which he sees occupies the position which the centre of the real image had at the middle of the exposure. But the observer may jump at an estimate before this moment, or, more probably, he may delay some short time after the shutter has fallen before he makes his estimate, as he continues to see the star and the wires for about $0^{\circ} 05$ longer. If he does the first his estimated position is too early and the concluded time of transit too great. If he does the latter, since the impressions on the retina made in the beginning of the exposure have then faded away, his estimated position is too late. The observer's quickness of perception, or the length of the *latent period* for him, may also have an effect on the personal equation, especially with the faintest stars.

This personal error seems to be that which is peculiar to the method proposed. One might, perhaps, estimate the equation for its correction at from $-0^{\circ} 01$ to $+0^{\circ} 03$, but experiment alone can give the real amount, and the extent of its variations.

(d.) There may possibly be also an error due to the observer's catching what may be called the *rhythm* of the successive appearances of the star and then making his estimate on the point where he imagines the star ought to be instead of on the actual star. But even if such an error be theoretically possible, it can hardly be so practically. For the observer can take his attention off the star while it is passing between the groups and is obliged to do so, if he records his estimates himself. Again the rhythm consists in the orderly arrangement in distance of the successively appearing images and the distance of the successive images changes with the declination of each star observed. Hence it would seem that practically the opportunity for the observer's forming a habit scarcely occurs. The case is quite different in eye and ear observations where the beat of the clock is always sounding in the observer's ear, even when he is recording and the interval of the beats is always the same, so that the observer forms the habit of imagining the beats and referring the star to what he imagines. Old observers sometimes find themselves counting seconds just as one finds himself imagining or humming a musical air. After a few trials they could probably make very fair observations without a clock at all, as far as the agreement *inter se* of the several wires is concerned.

(e.) We may make a comparison of these estimates as to what personal errors may be probably expected in the proposed method with Gonnessiat's very interesting analysis of the personal equation in eye and ear observations ⁽¹⁾.

(1) Op. cit. p. 166.

“ Rhythmic equation,	—0. 15	to	+0. 30,
Persistence of vision,	—0. 05	to	0. 00,
Psycho-physiological equation,	—0. 15	to	+0. 05,
Decimal equation,	—0. 05	to	+0. 05,
	—0. 40	to	+0. 40.”

The first of these equations is due to the cause mentioned near the end of the preceding paragraph. The third is due to the need of co-ordinating the impressions made on two different senses. These two will not occur in the proposed method.

11. Use of a Chronograph.—If the observed numbers are written down in the observing book during the observation by the observer himself it will be necessary to put the groups as far apart as the wires in a reticle for eye and ear observations. The number of estimates that may be made in succession within a group, will be only as many as the observer can remember with certainty. If there is another to record, as many estimates may be made as the strain of close attention by the observer will allow, since he needs to call out only the successive estimates, and the recorder can identify round seconds enough.

It does not seem difficult to construct a registering apparatus that will take the recorder's place by combining with a chronograph some form of typewriter that will print the estimated decimals on the chronograph sheet or strip. The printing of the decimals would be done by means of electro-magnets with a key board of ten keys (two for each finger), that the observer may lay in his lap or may have fastened to the side of the observing chair. As the chronograph is not needed for exact measurement of the time, it may be reduced to an apparatus that will print on a moving slip the successive seconds. There is no need here of great accuracy as there is in Prof. Hough's printing chronograph. The computation of the time of transit can be easily made directly from the numbers on the strip. The observer's signals will be later of course than the second to which they belong, but as the distance between the corresponding numbers will be nearly constant, there will be no trouble in identification.

The ordinary barrel chronograph may be used for the same purpose by so constructing the keys that by simply depressing them conventional signals are sent to the chronograph pen, which are translated into the corresponding decimals when the sheet is read off. When only a single pen is used it will be necessary to cut the clock out of the chronograph circuit while the signals for the estimates are being made, as the clock signal would confuse them. The round

seconds corresponding to the decimals can be made out from the clock signals on adjoining lines or may be determined simply by a graduated ruler.

12. *More than Three Wires in a Group.*—When a recorder is employed, either an assistant or the suggested apparatus, the number of wires in a group may be made more than three, and the number of estimates of the star's position made within a group will be limited only by the length of time the observer can continue to give close attention to his estimates. Care must be taken, however, that there is no confusion as to the two wires to which any estimate refers, by recording the omission of estimates by notes in the observing book, or by limiting the number of wires.

The interval between the different wires of a group should be, of course, that of the clock beats. (See No. 7, p. 152.) The interval between the group will be only enough to give the observer the needed rest.

13. *Some Other Modifications.*—Instead of increasing the number of wires, we may reduce it to two. This will give a simpler arrangement as far as merely the observing is concerned, and one that will still share some of the advantages of the proposed method.

Dispensing with the photochronograph or reducing the number of wires still further, will bring the method back to one of the methods mentioned in the first number of this chapter, and may make clearer the connection of the proposed method with prior methods.

If the photochronograph is suppressed and the star allowed to appear continuously, we have the method of Gonnessiat's experiments (No. 1, (e), page 146). Even in this case the use of three wires in a group would be an advantage.

If there be only single wires we have the method of the Paris and Lyons experiments and the Greenwich trials (No. 1, (c), page 145), with a very convenient form of shutter, the *bar photochronograph*. It may be remarked that for the suggested applications of the photochronograph it would be better to make the width of the bar less than its play up and down, so that no part of the field is always covered up by it.

The proposed method may also be combined with Prof. Langley's method (No. 1, (b), page 145). The signals of the auxiliary clock work which illuminate the field would be used for the electro-magnet of the photochronograph also, instead of the signals from the standard clock. The two sets of signals would be compared by means of a chronograph. The decimal to be estimated at each wire would not exceed ± 0.1 and the estimate would be rather whether at any wire the deviation from exact bisection was sensible or not. The combination of the two methods would eliminate the error that might arise in Langley's method from the star's

being always in sight, and also that arising from the unsteadiness of the star, as the average of the estimates would give the position of the mean image of the star with regard to the wires.

Any form of shutter can of course be used in the proposed method, which will give a very short exposure to the star. A form which seems to have some advantages would be a light horizontal strip which would be revolved by the signal from the clock about an axis lying parallel to the horizontal wires of the field.

14. Adaptation to the Meridian Circle.—In order to use this method of observing with the Meridian Circle, it is necessary to make provision for setting in declination. When a micrometer is used for the settings its motion must be limited to that part of the field which is covered by the shutter when the star is eclipsed. To secure this, a little care should be given to the circle setting, and it may possibly be well to return the micrometer to a fixed point before each observation. The shutter can be given a considerable breadth and its play increased by lengthening the armature arm. But as $2\text{ mm.} = 5'$ for a focal length of 137.5 cm. ($= 4\text{ ft. } 6\text{ in.}$), a great breadth will hardly be needed.

If the settings are made outside of the transit wires, the current can be broken during them and the shutter allowed to drop out of the way. If the settings are made while the star is passing through the middle group, the current can be broken between this and the preceding group, and the setting made so exact that it will be easy to complete it within the group, although the star is seen there only at a few moments; provided, of course, that it is possible to make the setting sufficiently exact while giving proper attention to the estimates for the transit. If the declination wires are sensibly straight and horizontal, the setting for the more rapidly moving stars can be made close up to the middle group, since the reduction to the meridian will be insensible there. For the slower stars there will be that much more time within the group.

15. Comparison with the Photographic Method.—If we compare the method of observing proposed in this paper with the photographic method for which the photochronograph was devised, and according to which observations have been carried on here for a year and a half, it will be seen that there is a close correspondence. In the photograph the successive, practically instantaneous, positions of the star are fixed on the plate over as much of the field as is desired. For the eye these positions are transient, but as many of them as can conveniently be handled are determined by what should be the most accurate method, viz: by reference to two fixed wires on either side of them. Each of the methods has its comparative advantages and disadvantages.

In the visual method the estimates of the successive positions of the star have to be

made quickly, although not too quickly, it is thought, for accuracy. In the photographic method the measures can be made with full deliberation and with all the conveniences of an ordinary room.

In the visual method when the observation is completed, all is done that can be done, and any criticism of the recorded numbers must rest on more or less probable conjectures. While it cannot be said that it will never be necessary to do this for the photographic plates, still the need is much less. For the photograph exhibits a permanent record, which can be re-examined at any time and by any method that promises the elimination of the personal equation, sure to intervene in measures by a person.

The vibration of the shutter before the eye in the visual method may somewhat disturb the observer in his estimates, even after he has become accustomed to it, and, on account of the persistence of vision, there will be also some little uncertainty about the exact moment to which each estimate corresponds; while the sensitive plate has no nerves to be disturbed, and the centre of each impressed image must correspond as exactly to the middle of the exposure as the granular nature of the film will allow.

On the other hand photography is not everywhere possible. Its use requires a special adaptation of lens and focal length and entails additional labor.

There is the added chance of failure in the photographic processes, though failures should be rare when the stars are clearly within the capabilities of the telescope and the sensitive plates employed. Still, with photography one does not know with full certainty what stars he has secured until his plates are developed. This may be a serious inconvenience when observations are carried on through clouds.

It would seem, therefore, that the visual method is more suited to general transit observations, and that the more accurate and more laborious photographic method will find its special application in such standard work as the determination of longitudes or the construction of fundamental star catalogues.

16. *Concluding Remarks*—The method of observation proposed here may possibly have been suggested before, although, as it stands, it has not been found. Its parts are not new and it is only a combination and extension of what is contained in Dr. Gonnessiat's paper.

It is not very satisfactory to publish methods of observation without at the same time giving actual results from their use. Still it has been thought advisable to describe this method in order to give a survey of the whole field within which the photochronograph may be applied.

ERRATA.

Page 35, line 3 from below, for 0.0147, read 0.0457.

Page 36, Corrigenda, line 2 from below to be cancelled.

Page 85, line 7 from below, for *were*, read *was*.

Page 85, line 1 from below, for *on*, read *in*.

Page 102, line 13 from below, for *of* the proper motion, read *or* etc.

Page 118, line 5, for *Differences*, read *Difference*.

Page 119, line 12, for *was*, read *were*.

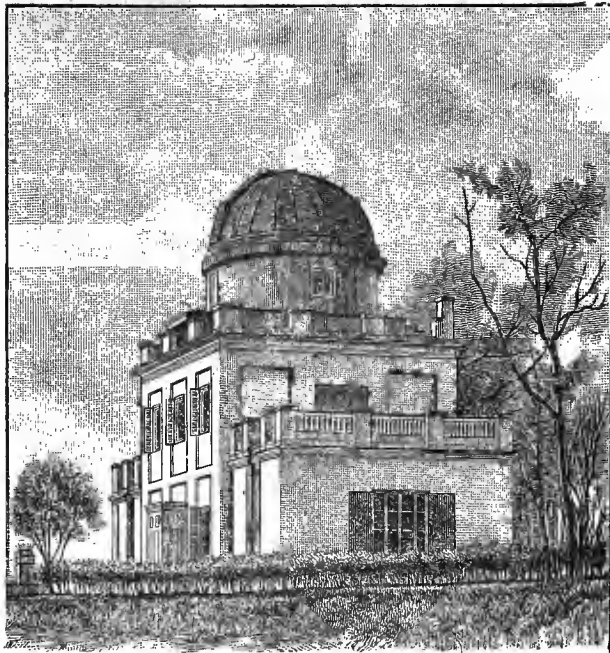
Page 119, line 4 from below, for *distances*, read *distance*.

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